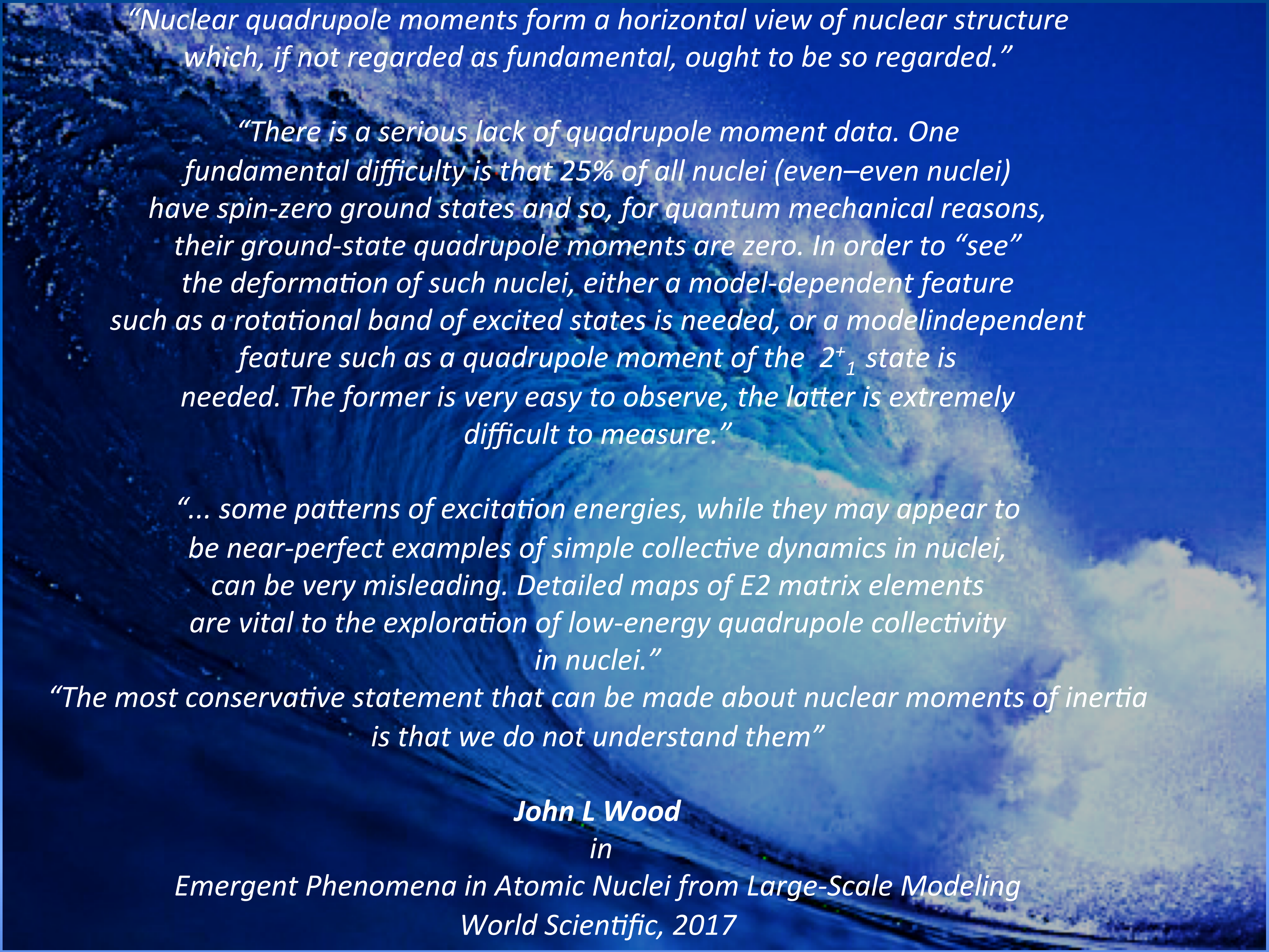
Do we understand nuclear collectivity?

Lifetime measurements for sensitive tests
of nuclear structure theories

Bo Cederwall
KTH - Royal Institute of Technology, Stockholm



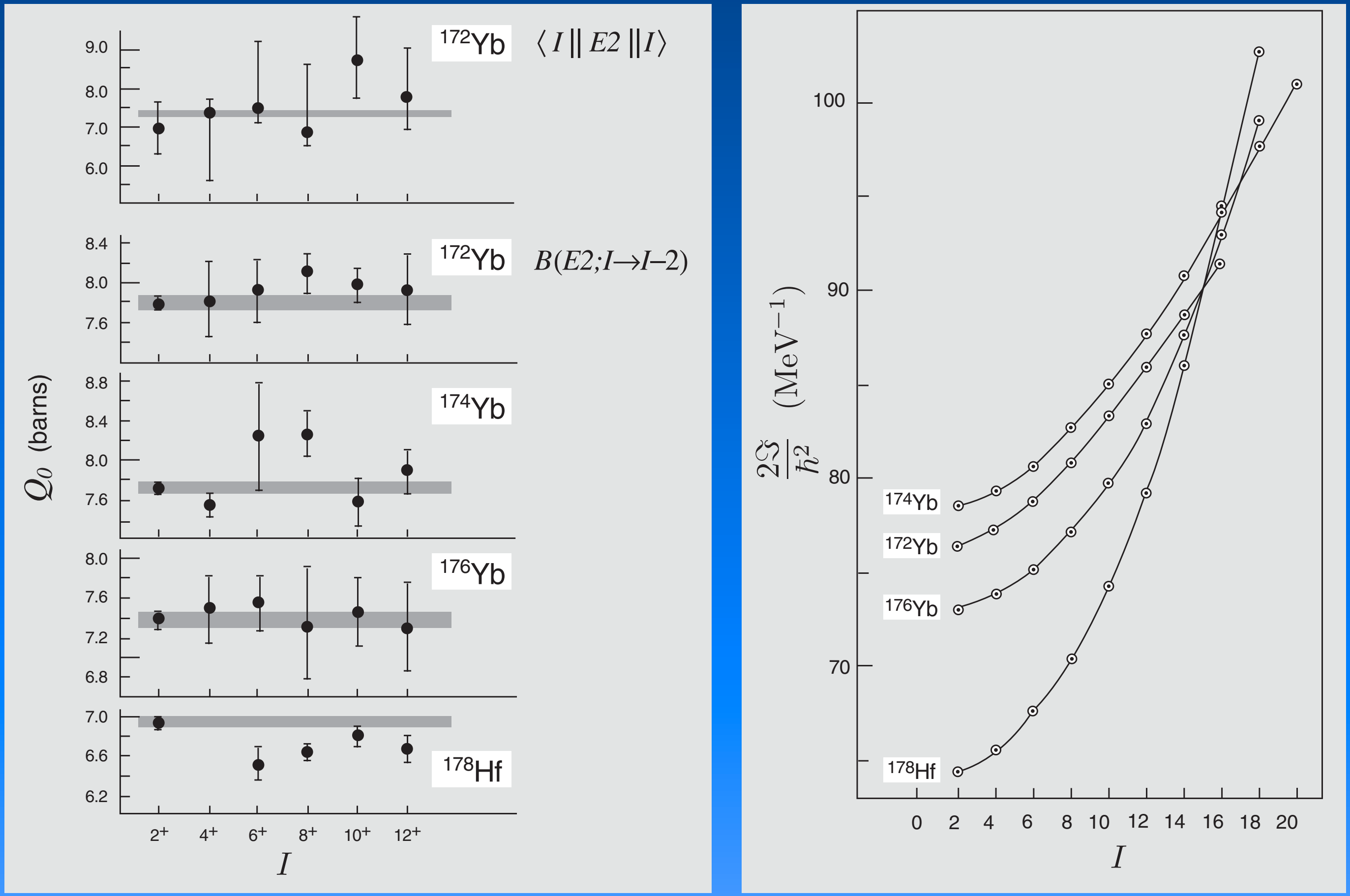
"Nuclear quadrupole moments form a horizontal view of nuclear structure which, if not regarded as fundamental, ought to be so regarded."

"There is a serious lack of quadrupole moment data. One fundamental difficulty is that 25% of all nuclei (even–even nuclei) have spin-zero ground states and so, for quantum mechanical reasons, their ground-state quadrupole moments are zero. In order to "see" the deformation of such nuclei, either a model-dependent feature such as a rotational band of excited states is needed, or a modelindependent feature such as a quadrupole moment of the 2^+_1 *state is needed. The former is very easy to observe, the latter is extremely difficult to measure."*

"... some patterns of excitation energies, while they may appear to be near-perfect examples of simple collective dynamics in nuclei, can be very misleading. Detailed maps of E2 matrix elements are vital to the exploration of low-energy quadrupole collectivity in nuclei."

"The most conservative statement that can be made about nuclear moments of inertia is that we do not understand them"

John L Wood
in
Emergent Phenomena in Atomic Nuclei from Large-Scale Modeling
World Scientific, 2017



(a) (b)

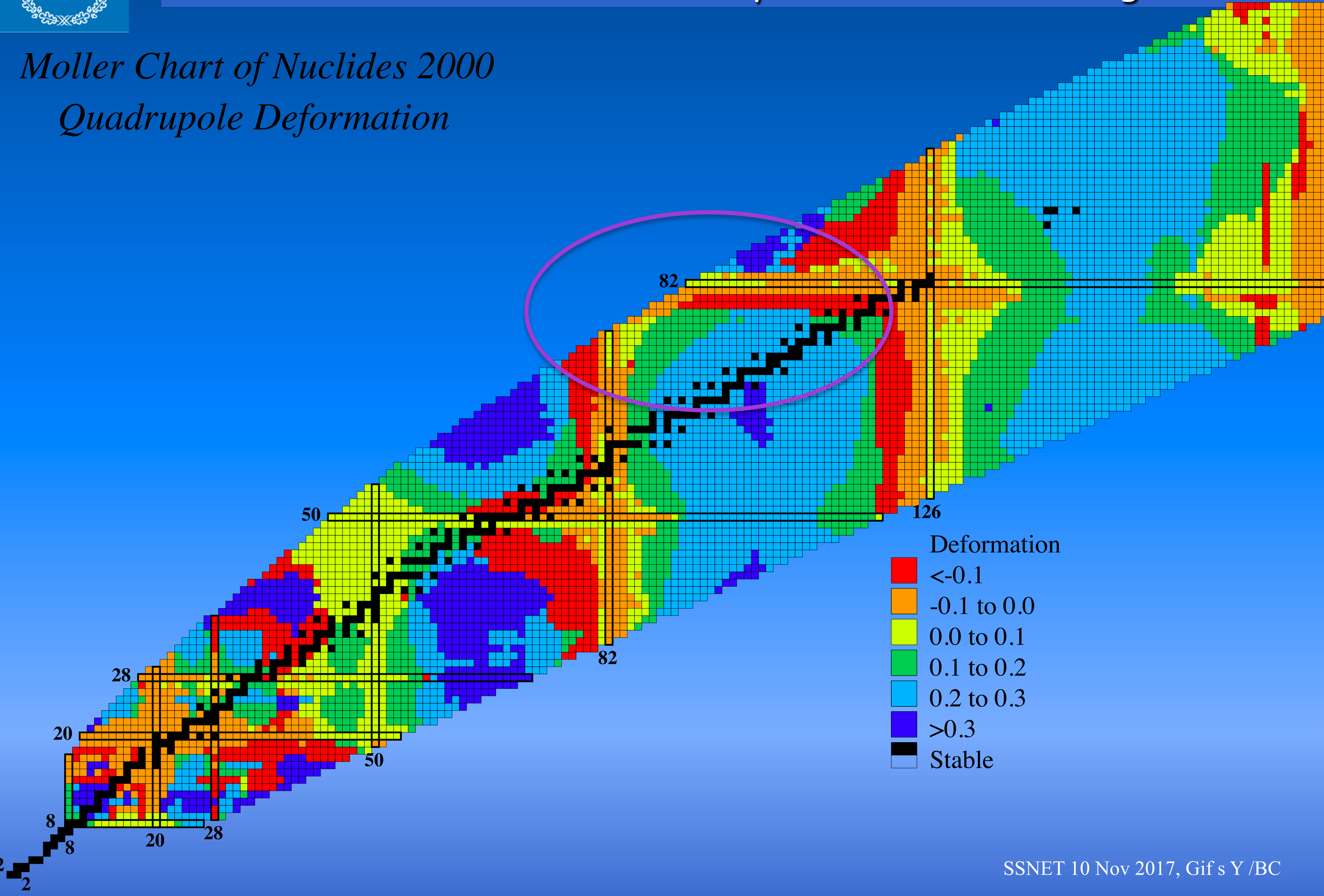
Fig. 7. (a) Intrinsic quadrupole moments, Q_0, for ^{172,174,176}Yb and ^{178}Hf extracted using rotor-model relationships for $E2$ matrix elements. The figure is taken from Ref. [17]. (b) Moments of inertia for ^{172,174,176}Yb and ^{178}Hf extracted using rotor-model relationships for the energies. The figure is taken from Ref. [17].

D. J. Rowe and J. L. Wood, Fundamentals of nuclear models: Foundational models. Chapter 6, World Scientific, Singapore (2010)

Part I: $B(E2:2^+ \rightarrow 0^+)$ in ^{162,164}W and evolution of collectivity in the rare earth region

Moller Chart of Nuclides 2000

Quadrupole Deformation



- Plunger measurements using JurogamII+RITU+DPUNS @ JYFL
- Theoretical predictions using various theoretical approaches:

TRS-Woods-Saxon

Z.X.Xu and C.Qi, Phys. Lett. B 724, 247 (2013).
Z. Wu et al., Phys. Rev. C 92, 024306 (2015).

FRDM

P. Möller et al., At. Data Nucl. Data Tables 109-110, 1-204 (2016).

Skyrme Hartree-Fock-Bogoliubov

E. Chabanat, H. Bonche et al., Nucl. Phys. A, 635, 231 (1998).
M. Kortelainen et al., Phys. Rev. C 82, 024313 (2010); Phys. Rev. C 85, 024304 (2012); Phys. Rev. C 89, 054314 (2014)
M. V. Stoitsov et al., Comput. Phys. Commun. 184, 1592 (2013).

Skyrme HFB24 mass model

S. Goriely et al., Phys Rev C 88, 0243080 (2013).

Relativistic Mean Field

T. Niksic et al., Comput. Phys. Commun. 185, 1808 (2014).
G.A. Lalazissis et al., Phys. Rev. C 71, 024312 (2005).

Gogny Hartree-Fock-Bogoliubov + GCM (BMF)

G.F. Bertsch et al., Phys Rev Lett 99, 032502 (2007).

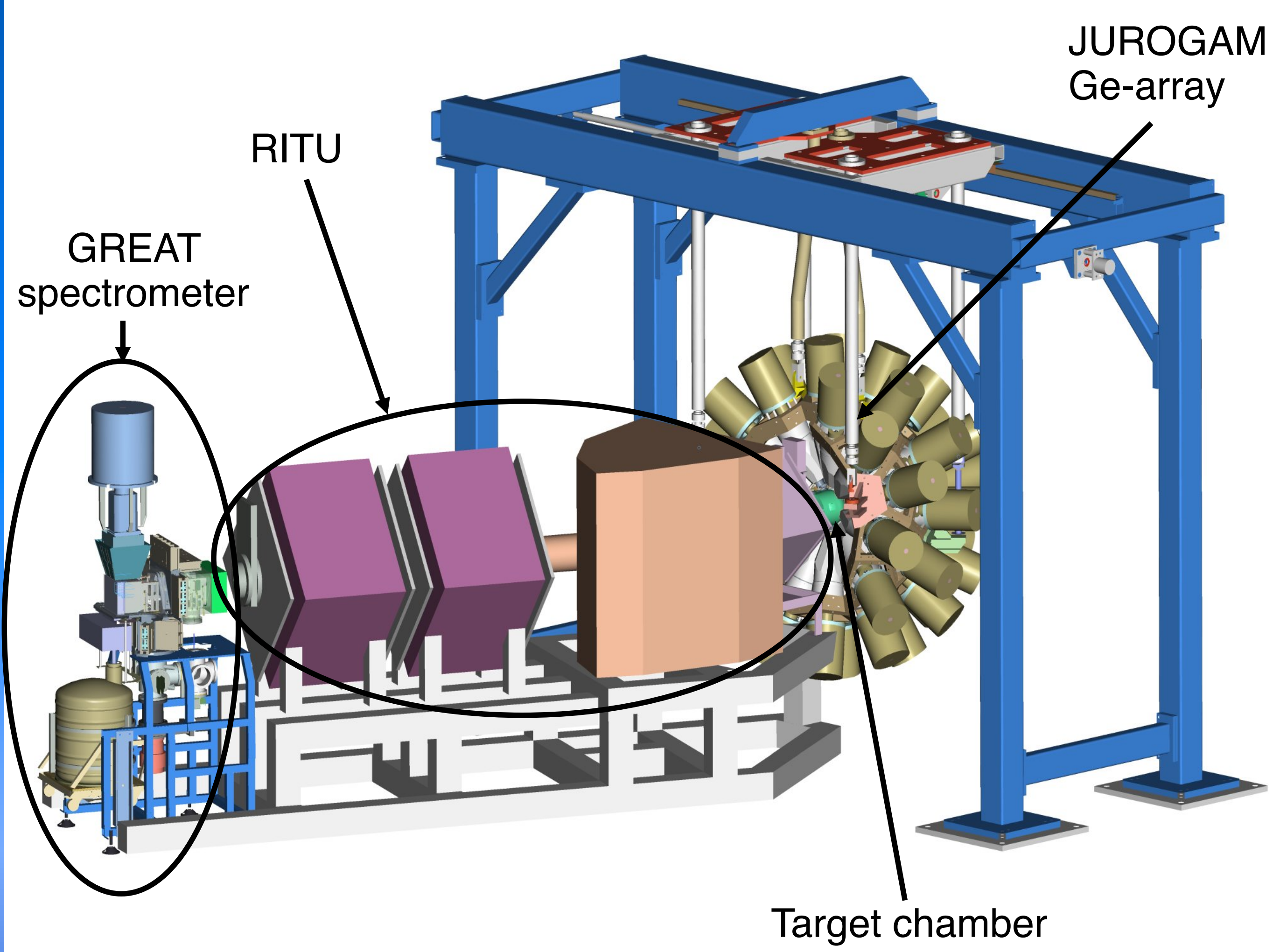
Deformed QRPA

D.S. Delion and J. Suhonen, Phys. Rev. C 87, 024309 (2013)

Coherent State Model

D.S. Delion and A. Dumitrescu, At. Data Nucl. Data Tables 101, 1 (2016)
P.O. Lipas, P. Haapakoski, T. Honkaranta, Phys. Scripta 13, 339 (1976)

Experimental set-up at JYFL
Univ. of Jyväskylä Cyclotron Laboratory

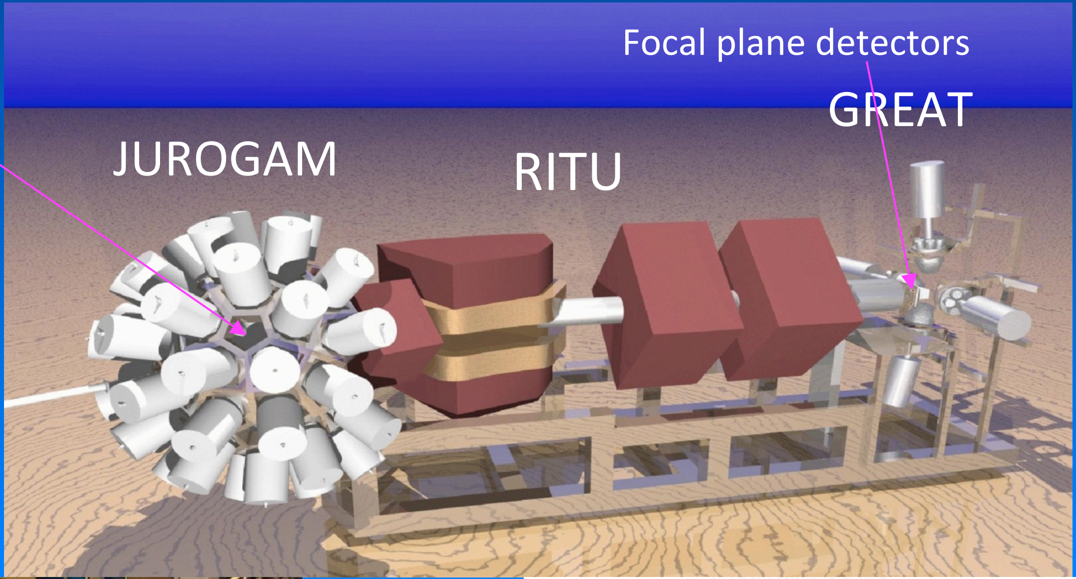


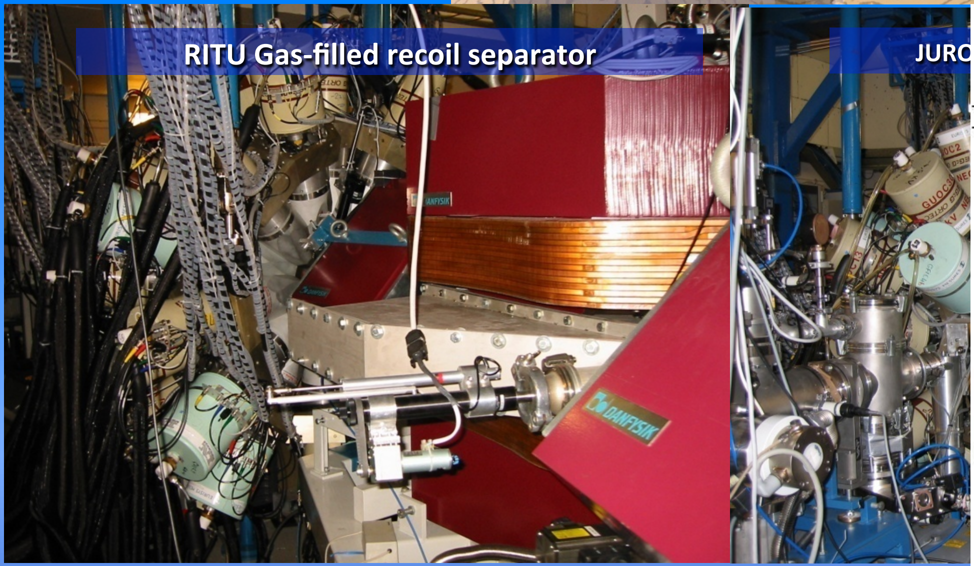
Recoil-decay tagging at JYFL – JUROGAM-RITU

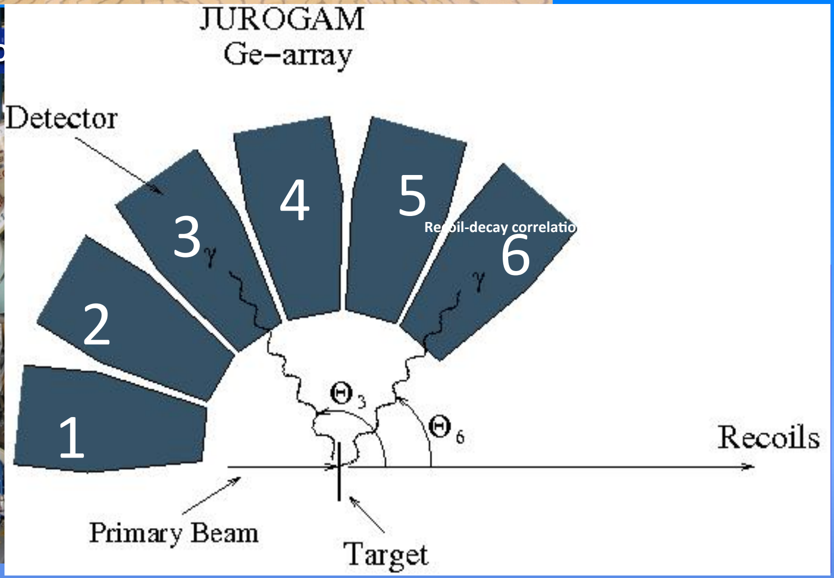
Detection of prompt gamma rays

43 detector HPGe
EUROBALL phase I type

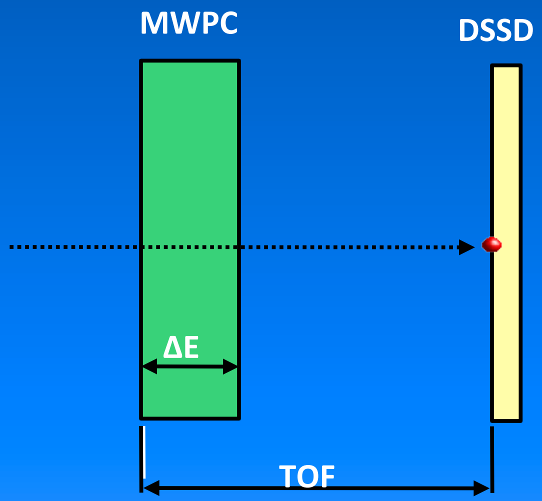
Total photo-peak efficiency
4.2% at 1.3 MeV
→ 6% with JUROGAM II

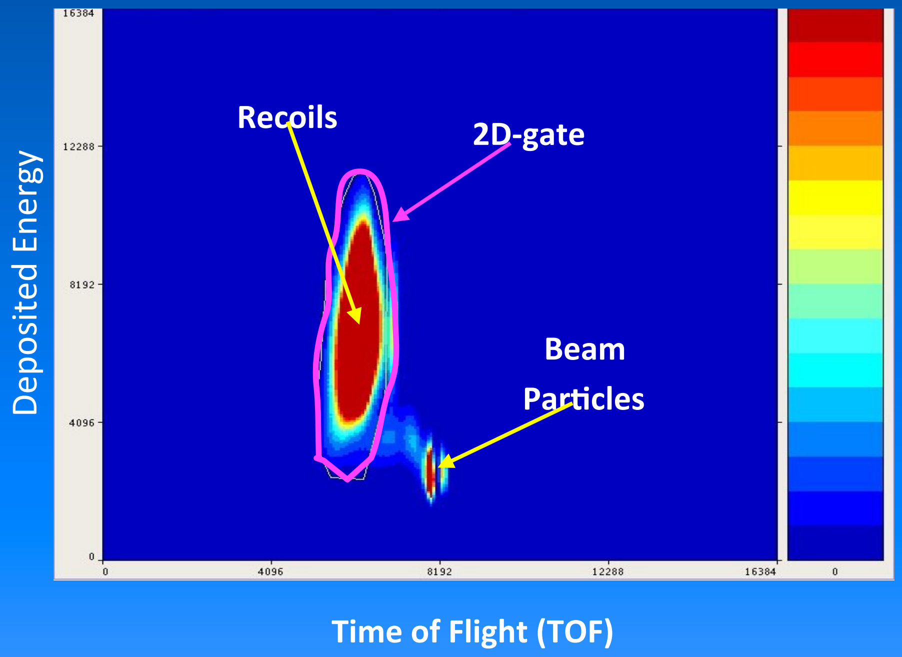






Recoil selection

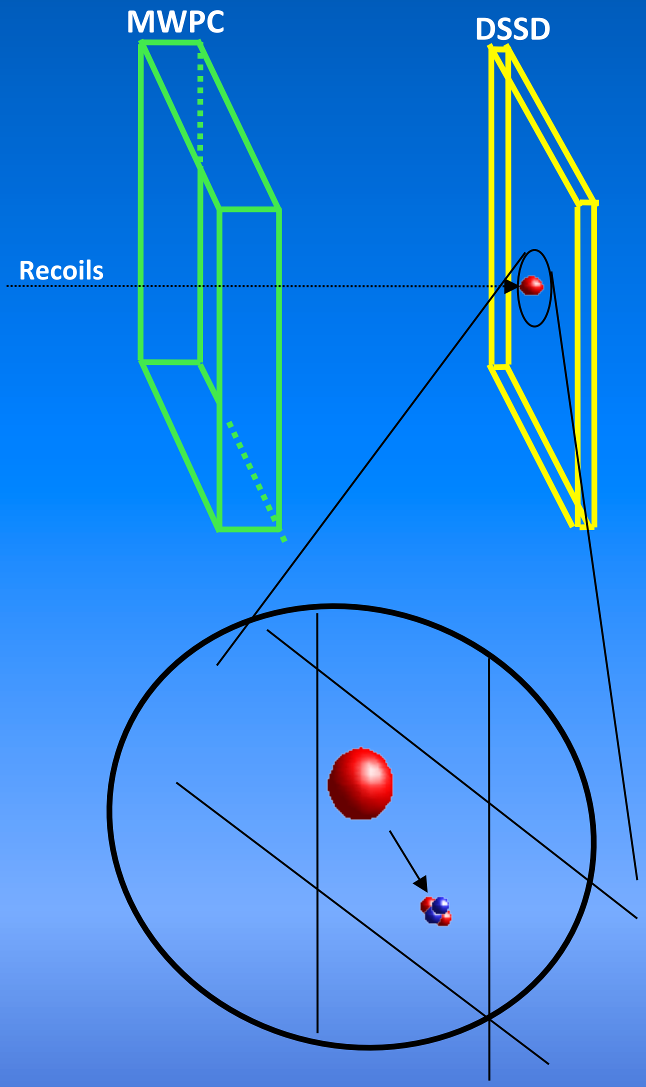


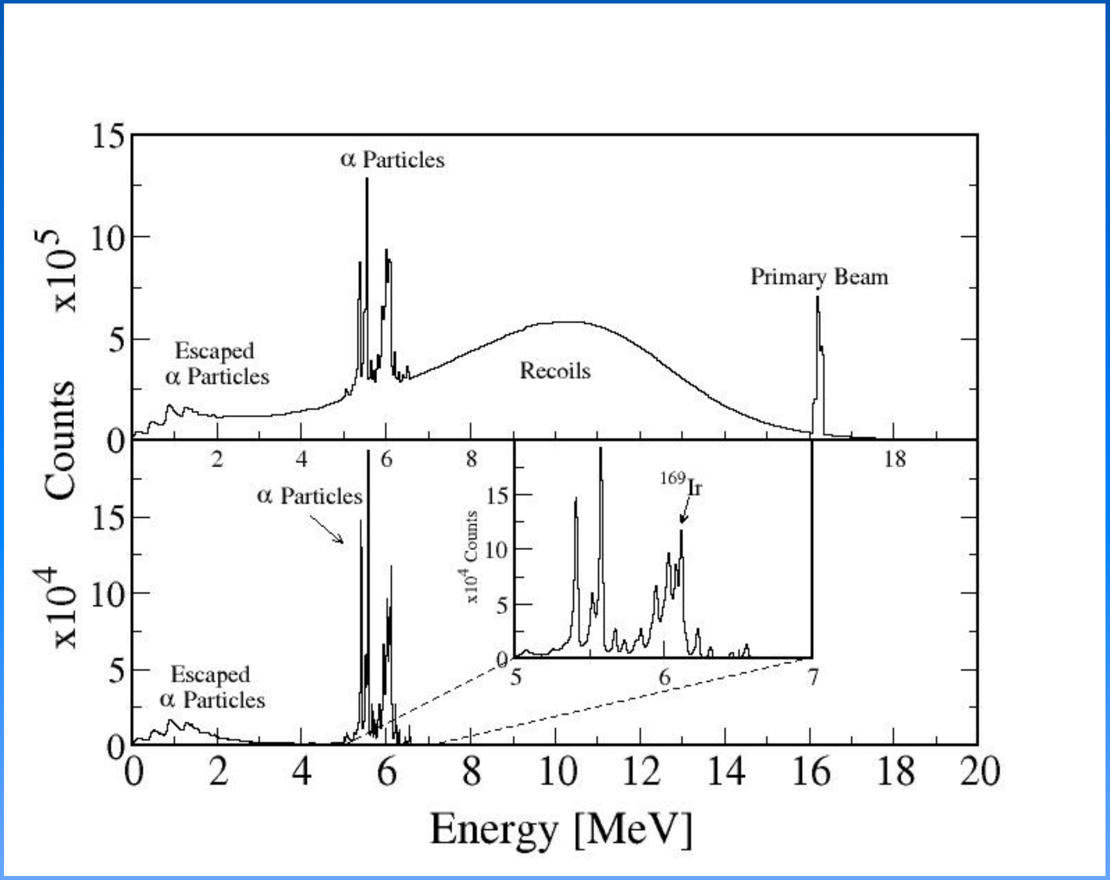


Recoil identification by means of energy loss (ΔE) and time-of-flight consideration

Anything not passing the 2D TOF-DE gate is vetoed

Charged particle detection and recoil identification

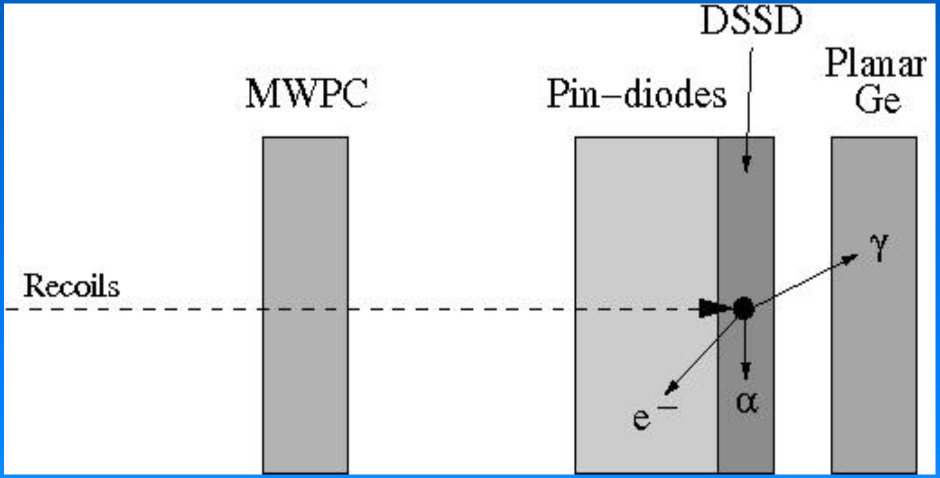




The MWPC acts as a veto detector for identification of recoil-decay products

Anything NOT passing the MWPC is a delayed decay event identifying the recoil

Gamma Recoil Electron Alpha Tagging - GREAT

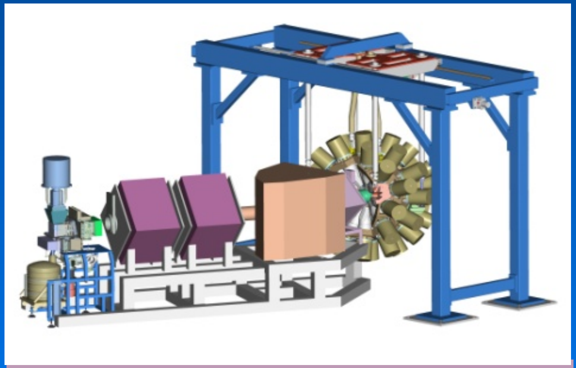


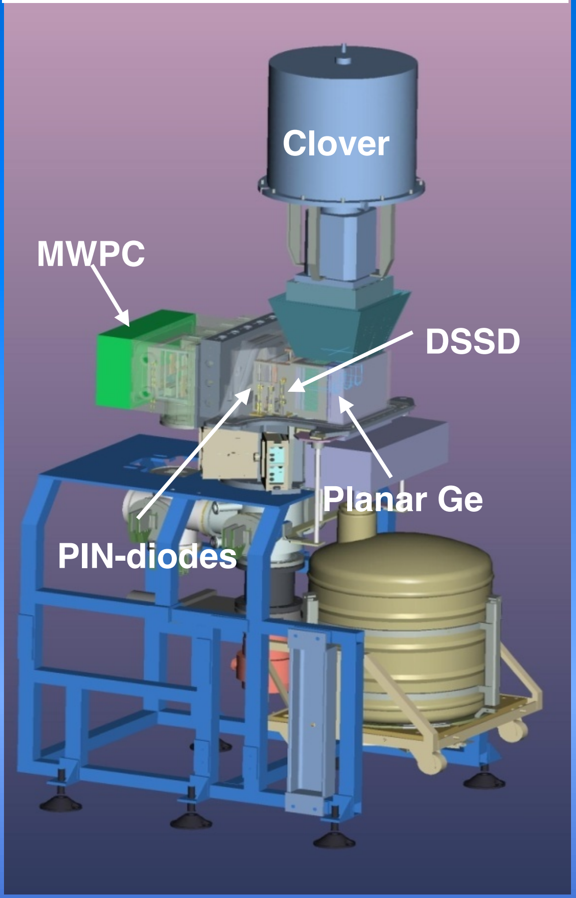
MWPC - Multi Wire Proportional Counter: Recoil discriminator

PIN-diodes: Detection of β-particles and conversion e^-

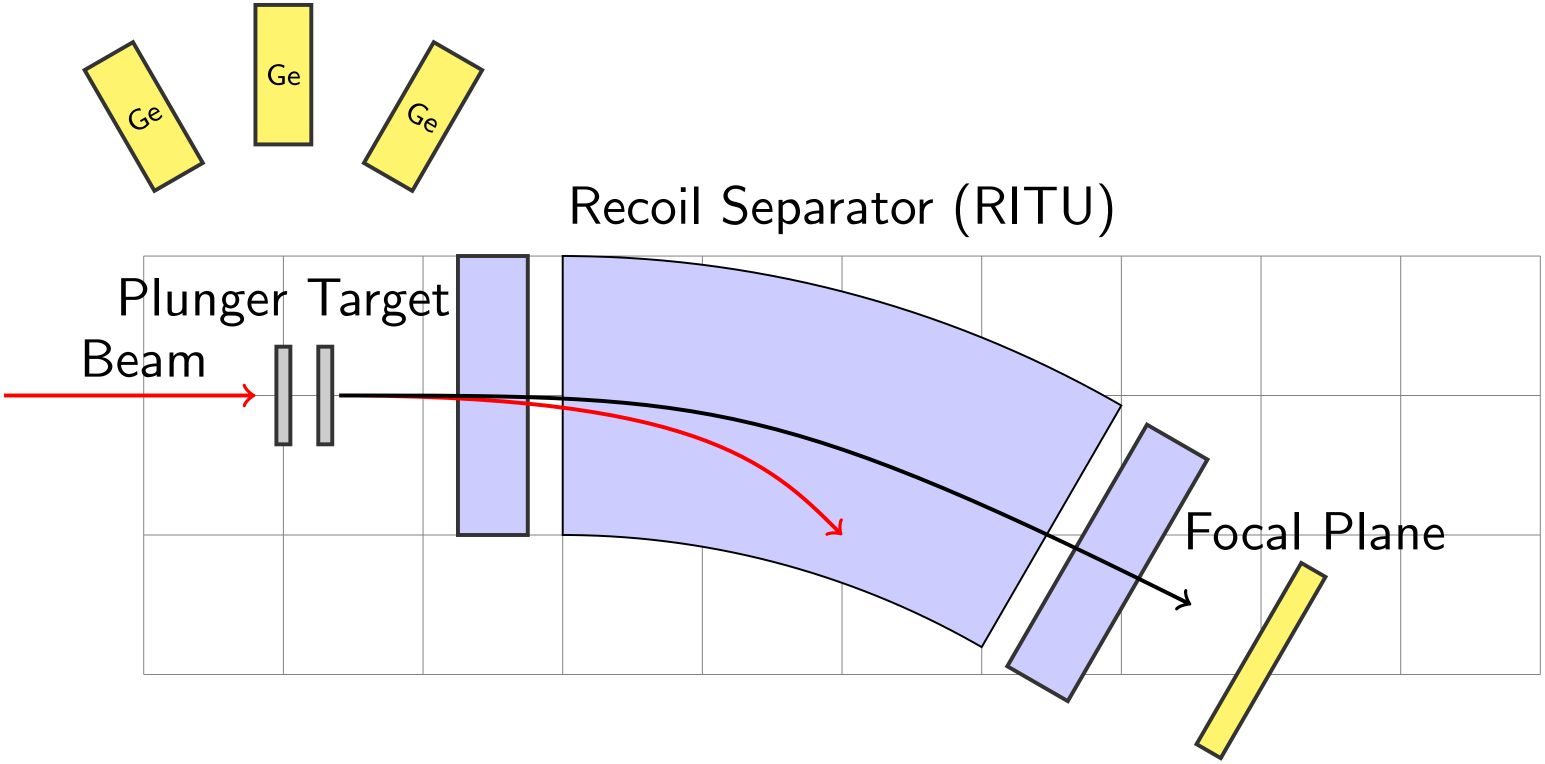
DSSD - Double-sided Silicon Strip Detector: Charged particle detection (alpha, proton)

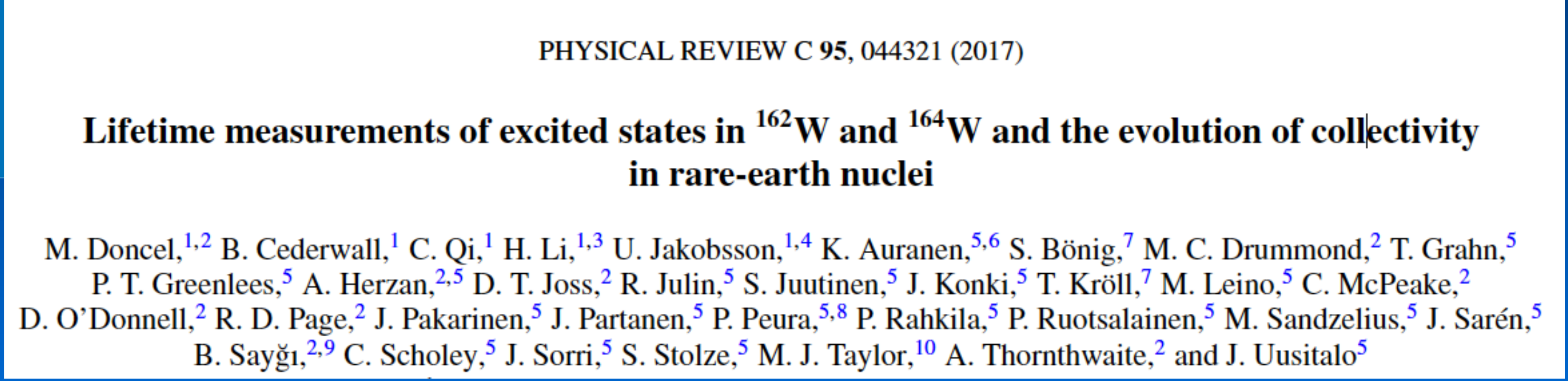
Planar Ge and Clover: Detection of delayed gamma rays following radioactive decays or from isomeric states





Recoil Decay Tagging combined with a differential plunger

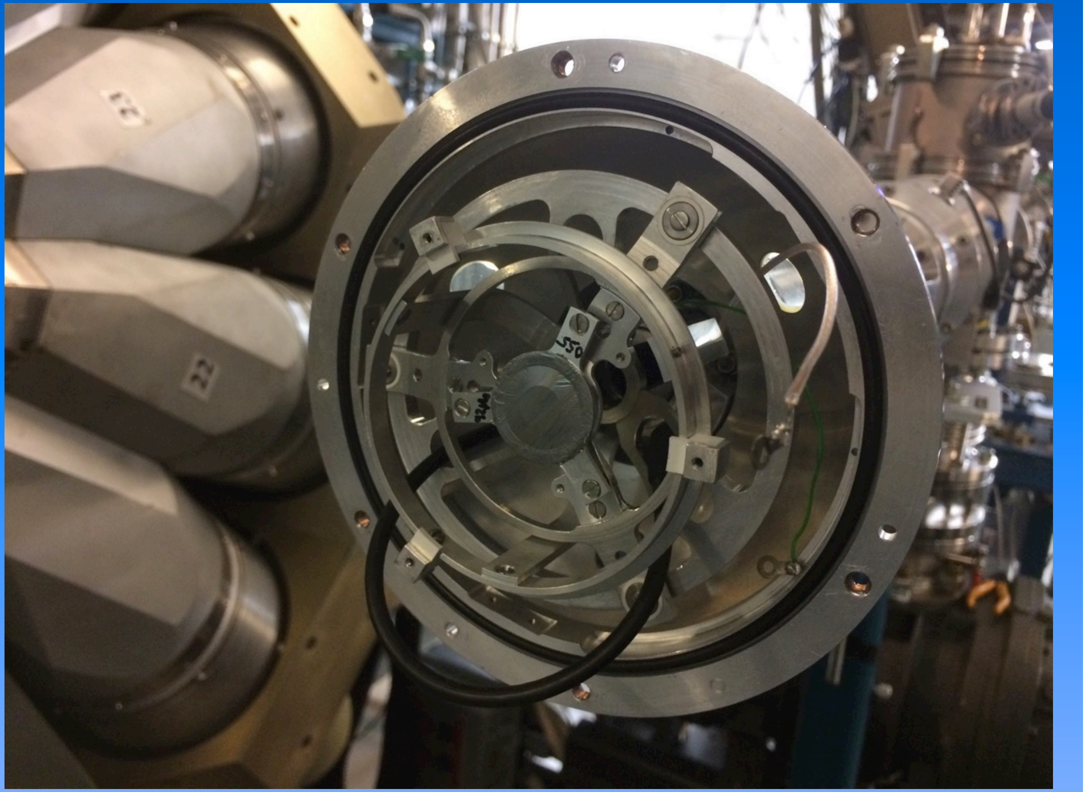


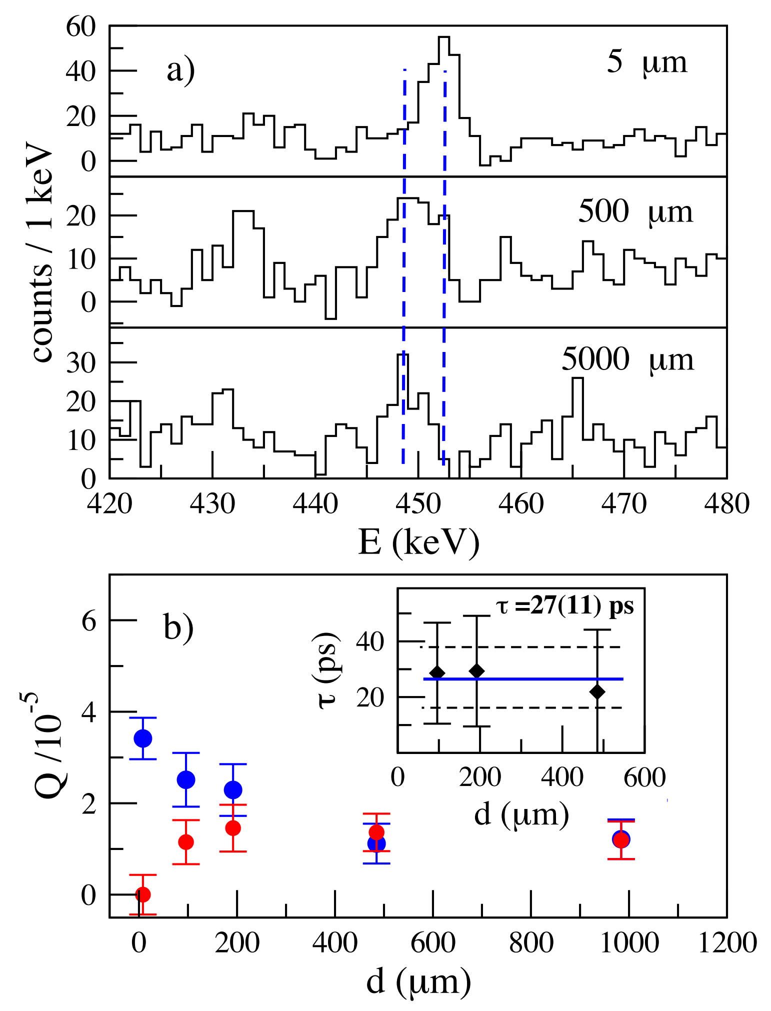


PHYSICAL REVIEW C **95**, 044321 (2017)

Lifetime measurements of excited states in ^{162}W and ^{164}W and the evolution of collectivity in rare-earth nuclei

M. Doncel,[1,2] B. Cederwall,[1] C. Qi,[1] H. Li,[1,3] U. Jakobsson,[1,4] K. Auranen,[5,6] S. Bönig,[7] M. C. Drummond,[2] T. Grahn,[5] P. T. Greenlees,[5] A. Herzan,[2,5] D. T. Joss,[2] R. Julin,[5] S. Juutinen,[5] J. Konki,[5] T. Kröll,[7] M. Leino,[5] C. McPeake,[2] D. O'Donnell,[2] R. D. Page,[2] J. Pakarinen,[5] J. Partanen,[5] P. Peura,[5,8] P. Rahkila,[5] P. Ruotsalainen,[5] M. Sandzelius,[5] J. Sarén,[5] B. Sayğı,[2,9] C. Scholey,[5] J. Sorri,[5] S. Stolze,[5] M. J. Taylor,[10] A. Thornthwaite,[2] and J. Uusitalo[5]

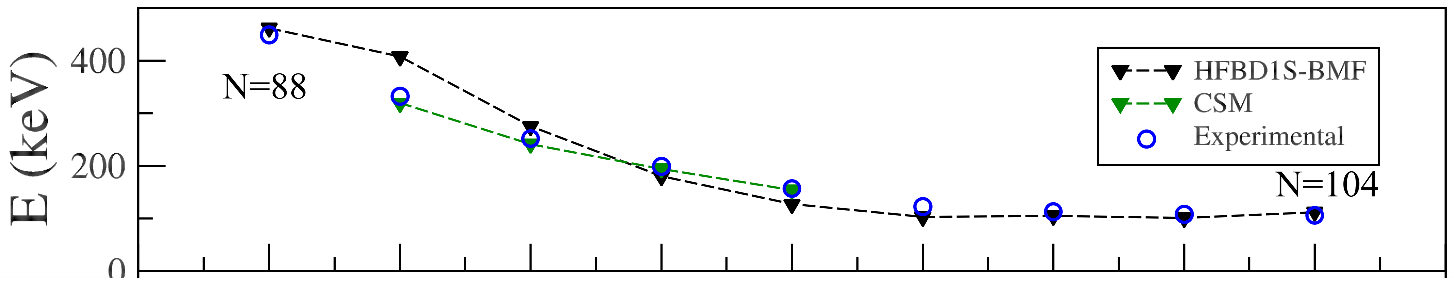




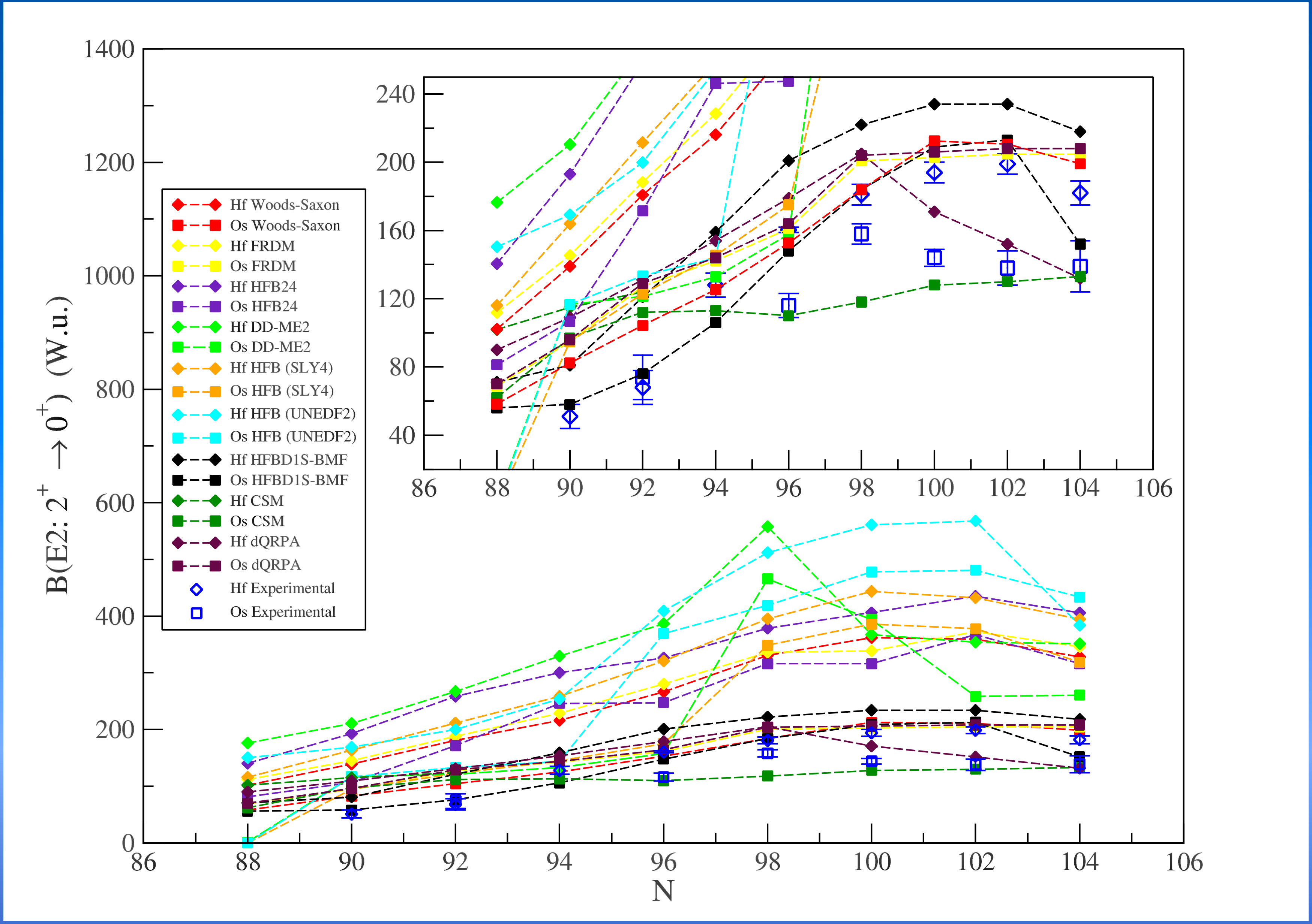
JR109: ^{92}Mo(^{78}Kr,2α)^{162}W @ 380 MeV

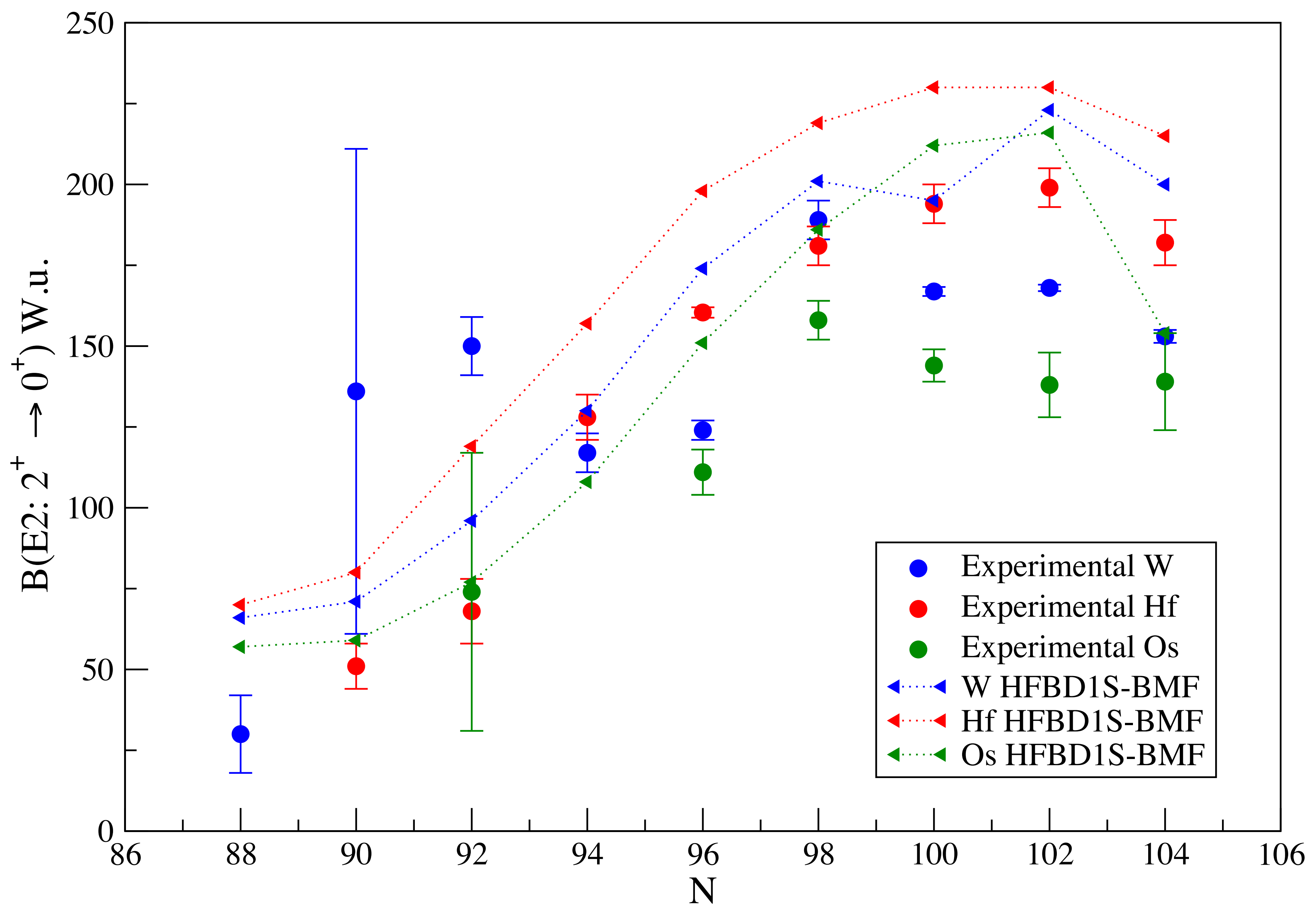
18 neutrons away from stability

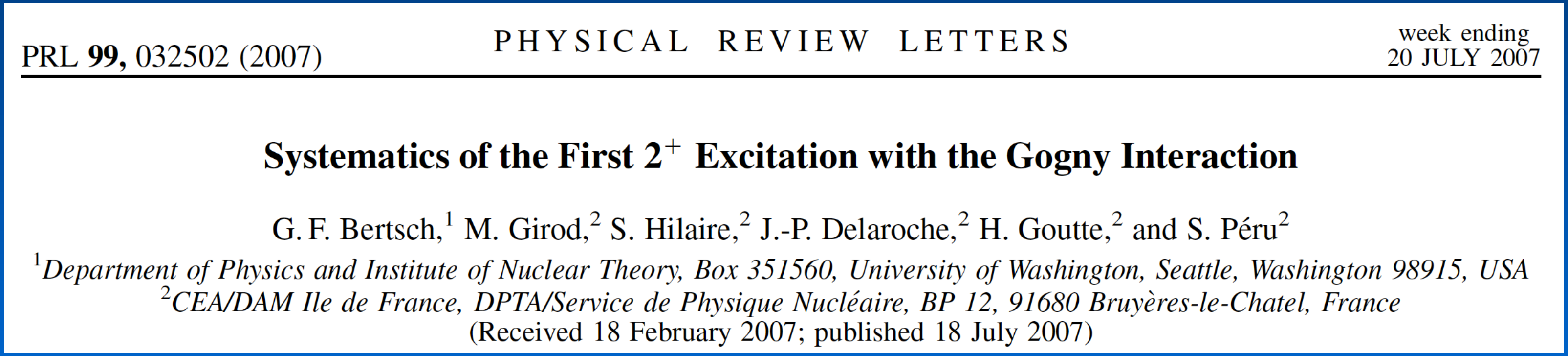
Predictions of B(E2:2⁺ → 0⁺) in W vs expt



Predictions of $B(E2:2^+ \rightarrow 0^+)$ in Hf, Os vs expt




B(E2: 2+ → 0+) W.u.
0
50
100
150
200
250
N
86
88
90
92
94
96
98
100
102
104
106
Experimental W
Experimental Hf
Experimental Os
W HFBD1S-BMF
Hf HFBD1S-BMF
Os HFBD1S-BMF



PRL **99,** 032502 (2007) PHYSICAL REVIEW LETTERS week ending 20 JULY 2007

Systematics of the First 2^+ Excitation with the Gogny Interaction

G. F. Bertsch,[1] M. Girod,[2] S. Hilaire,[2] J.-P. Delaroche,[2] H. Goutte,[2] and S. Péru[2]

[1]*Department of Physics and Institute of Nuclear Theory, Box 351560, University of Washington, Seattle, Washington 98915, USA*
[2]*CEA/DAM Ile de France, DPTA/Service de Physique Nucléaire, BP 12, 91680 Bruyères-le-Chatel, France*

(Received 18 February 2007; published 18 July 2007)

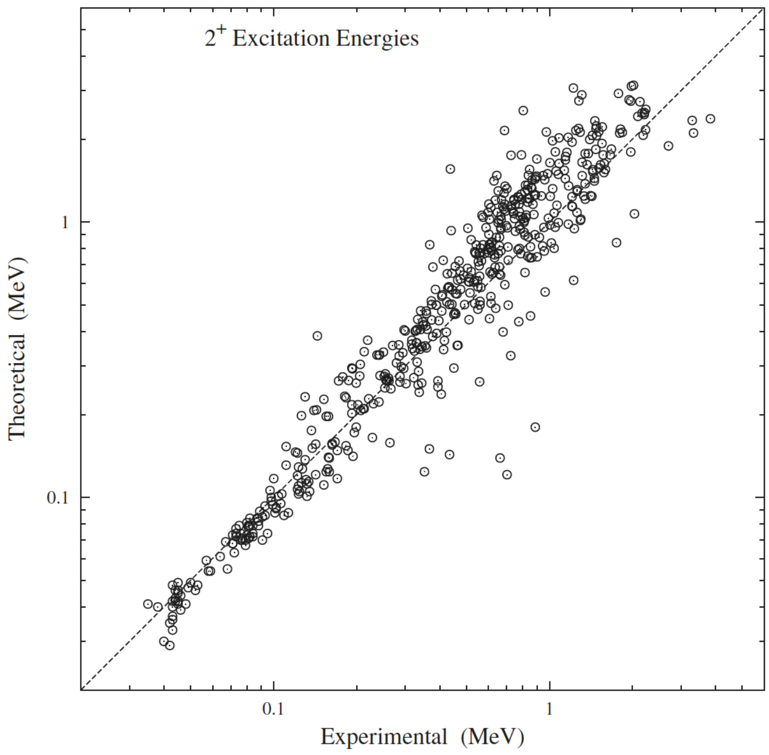
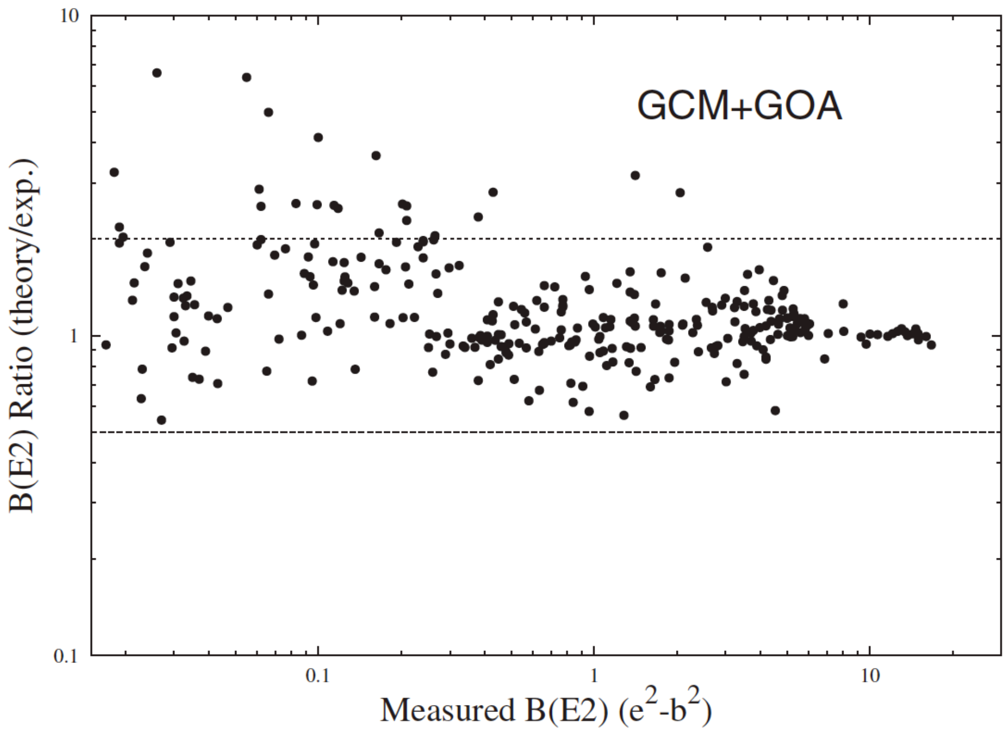
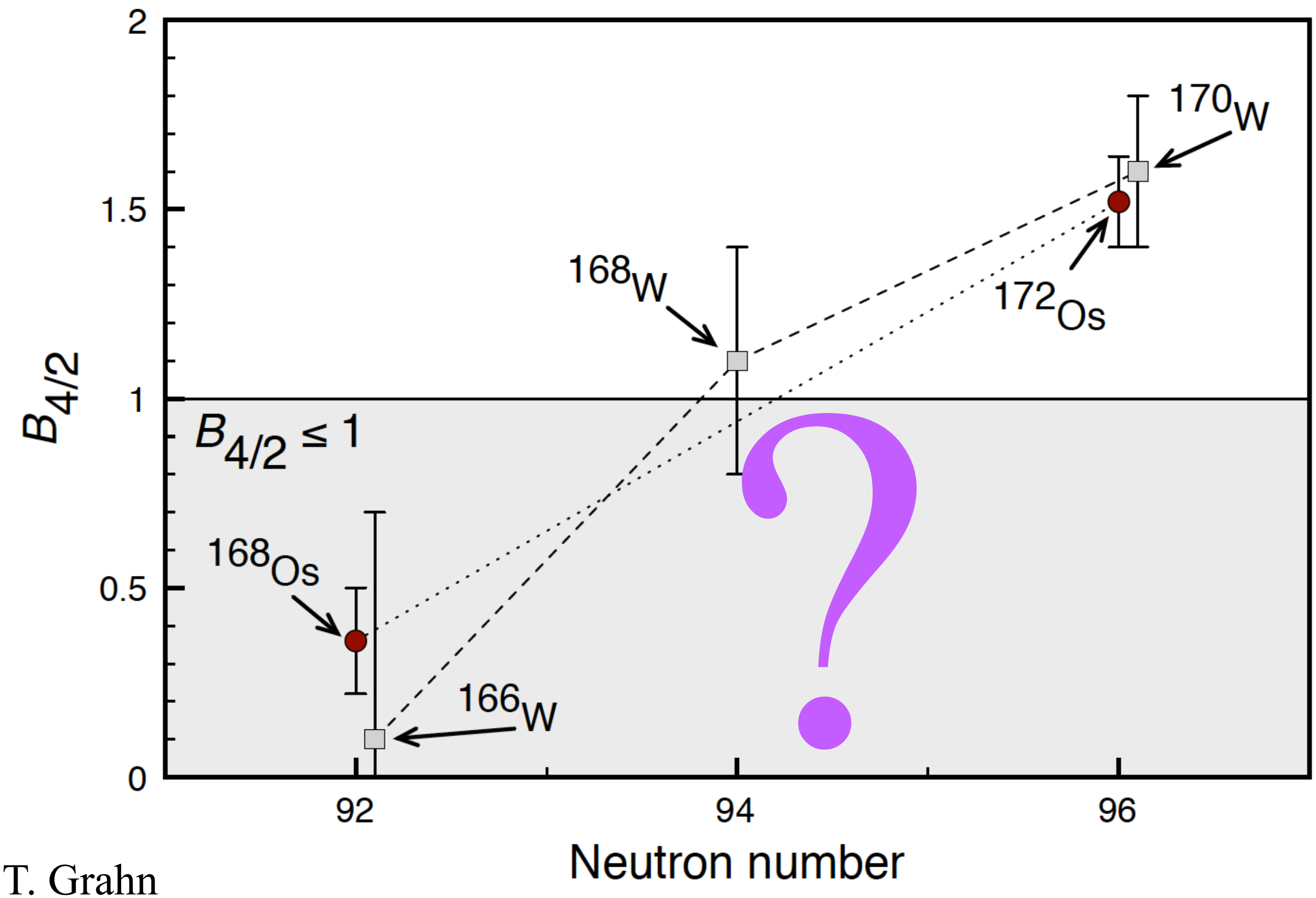


FIG. 1. Scatter plot of 519 even-even nuclei as a function of their experimental and theoretical 2^+ excitation energies.





T. Grahn

T. Grahn et al., Data from the JYFL JR74 experiment

A. Virtanen et al., Nucl. Phys. A 591, 145 (1995).

G. D. Dracoulis et al., Phys. Rev. C, 1576 (1984).

F. K. McGovan et al., Nucl. Phys. A580, 335 (1994).

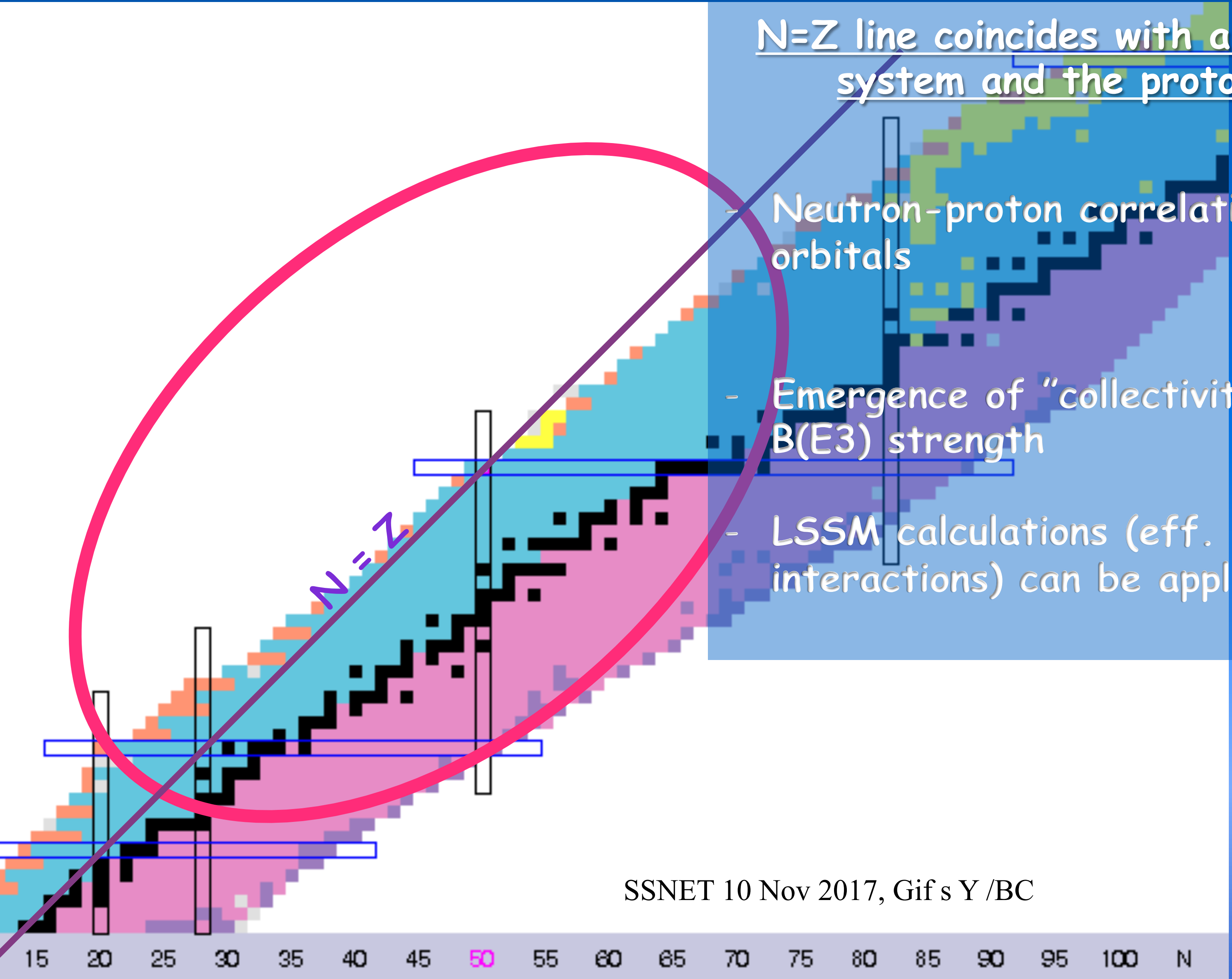
See talk by Tuomas Grahn!

Do we understand nuclear collectivity ?

State-of-the art models show striking deficiencies

Ab initio?
EFT?

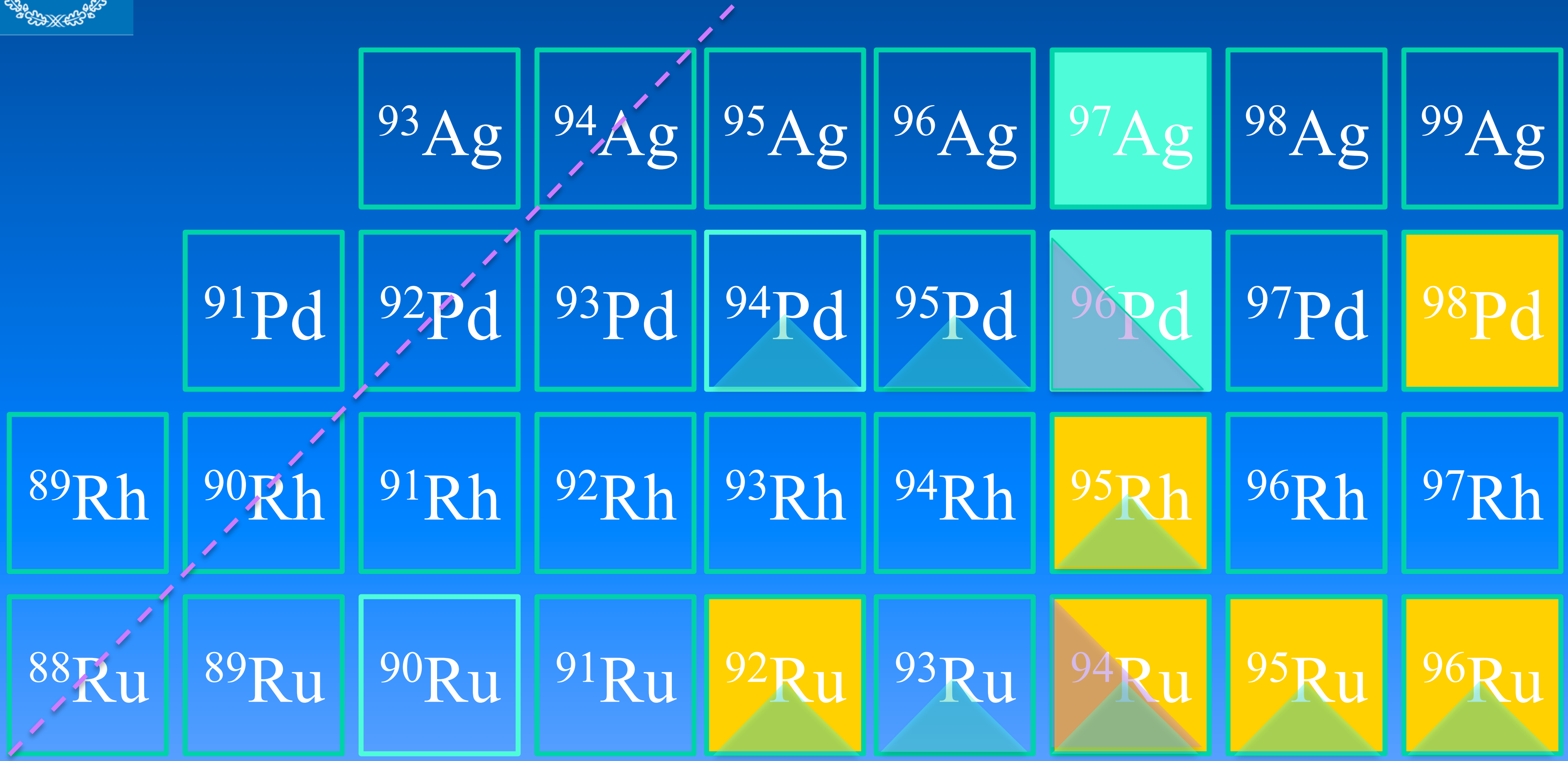
Part II: Nuclear structure around ^{100}Sn – near the "top" of the N=Z line



N=Z line coincides with a doubly-magic system and the proton dripline

- Neutron-proton correlations in identical orbitals
- Emergence of "collectivity"; B(E2), B(E3) strength
- LSSM calculations (eff. charges, interactions) can be applied and tested

Overview of lifetime measurements of low-spin states SW of ^{100}Sn



		^{93}Ag	^{94}Ag	^{95}Ag	^{96}Ag	^{97}Ag	^{98}Ag	^{99}Ag
	^{91}Pd	^{92}Pd	^{93}Pd	^{94}Pd	^{95}Pd	^{96}Pd	^{97}Pd	^{98}Pd
^{89}Rh	^{90}Rh	^{91}Rh	^{92}Rh	^{93}Rh	^{94}Rh	^{95}Rh	^{96}Rh	^{97}Rh
^{88}Ru	^{89}Ru	^{90}Ru	^{91}Ru	^{92}Ru	^{93}Ru	^{94}Ru	^{95}Ru	^{96}Ru

🟪 Fast timing
🟨 RDDS
🟩 Ge timing

FT
^{96}Pd: limit 2^+, value 4^+,6^+,8

RDDS
^{98}Pd: limit 2^+, value 4^+,6^+,8^+
^{95}Rh: 7 limits, value 9 states
^{92}Ru: 9 limits, value 8 states
^{94}Ru: 7 limits, value 10 states
^{95}Ru: 15 limits, value 11 states
^{96}Ru: 2 limits, value 11 states

B(E2) measurements provide critical tests of theory in the N≈50, A≈90 region

Data from H. Mach et al. (GANIL data, unpub.)
and ENSDEF)
Calculations by H. Grawe (A. Korgul et al, PRC 2017.)

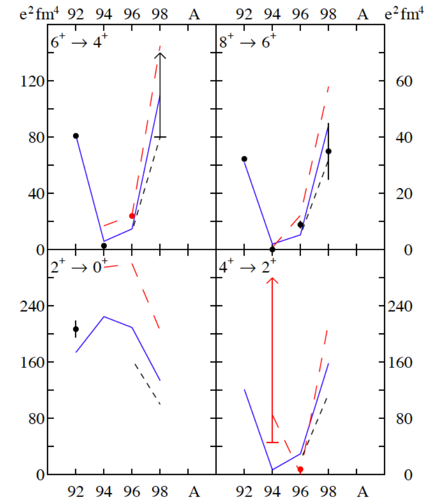


FIG. 4: Experimental B(E2) strengths for yrast transitions in even N=50 isotones in comparison to shell model predictions in the proton $(f_{5/2}, p, g_{9/2})$ model space for the approaches SMLB (full line) and SMCC (short dashed). The calculation including excitations of the ^{100}Sn is shown as long dashed line. Data are from present work and [23]

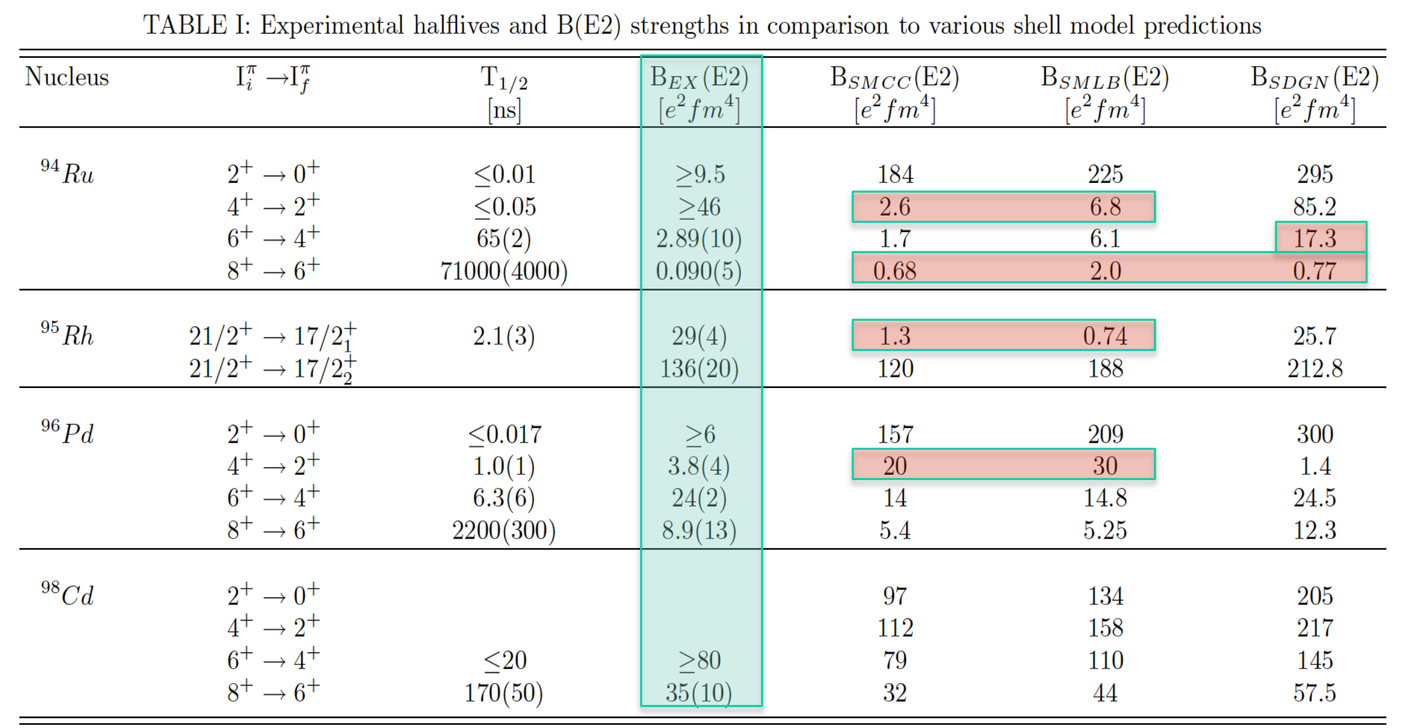
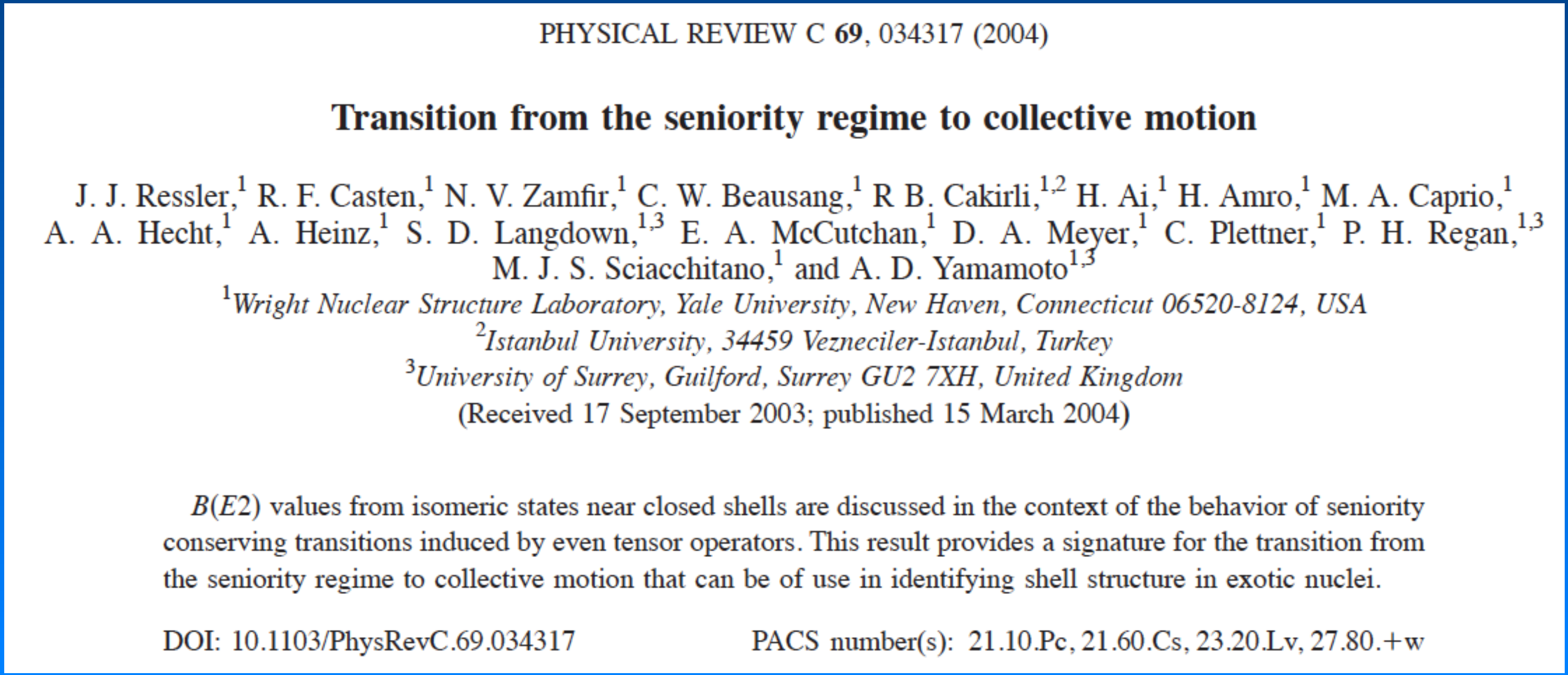


TABLE I: Experimental halflives and B(E2) strengths in comparison to various shell model predictions

Nucleus	$I_i^\pi \to I_f^\pi$	$T_{1/2}$ [ns]	B_{EX}(E2) [e^2fm^4]	B_{SMCC}(E2) [e^2fm^4]	B_{SMLB}(E2) [e^2fm^4]	B_{SDGN}(E2) [e^2fm^4]
^{94}Ru	$2^+ \to 0^+$	≤0.01	≥9.5	184	225	295
	$4^+ \to 2^+$	≤0.05	≥46	2.6	6.8	85.2
	$6^+ \to 4^+$	65(2)	2.89(10)	1.7	6.1	17.3
	$8^+ \to 6^+$	71000(4000)	0.090(5)	0.68	2.0	0.77
^{95}Rh	$21/2^+ \to 17/2_1^+$	2.1(3)	29(4)	1.3	0.74	25.7
	$21/2^+ \to 17/2_2^+$		136(20)	120	188	212.8
^{96}Pd	$2^+ \to 0^+$	≤0.017	≥6	157	209	300
	$4^+ \to 2^+$	1.0(1)	3.8(4)	20	30	1.4
	$6^+ \to 4^+$	6.3(6)	24(2)	14	14.8	24.5
	$8^+ \to 6^+$	2200(300)	8.9(13)	5.4	5.25	12.3
^{98}Cd	$2^+ \to 0^+$			97	134	205
	$4^+ \to 2^+$			112	158	217
	$6^+ \to 4^+$	≤20	≥80	79	110	145
	$8^+ \to 6^+$	170(50)	35(10)	32	44	57.5



PHYSICAL REVIEW C **69**, 034317 (2004)

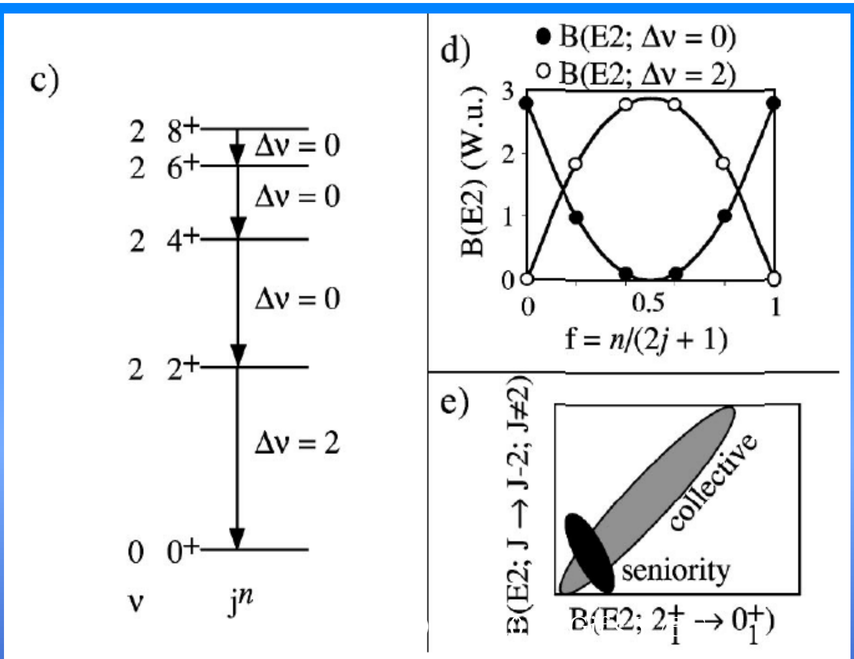
Transition from the seniority regime to collective motion

J. J. Ressler,[1] R. F. Casten,[1] N. V. Zamfir,[1] C. W. Beausang,[1] R B. Cakirli,[1,2] H. Ai,[1] H. Amro,[1] M. A. Caprio,[1] A. A. Hecht,[1] A. Heinz,[1] S. D. Langdown,[1,3] E. A. McCutchan,[1] D. A. Meyer,[1] C. Plettner,[1] P. H. Regan,[1,3] M. J. S. Sciacchitano,[1] and A. D. Yamamoto[1,3]
[1]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520-8124, USA*
[2]*Istanbul University, 34459 Vezneciler-Istanbul, Turkey*
[3]*University of Surrey, Guilford, Surrey GU2 7XH, United Kingdom*

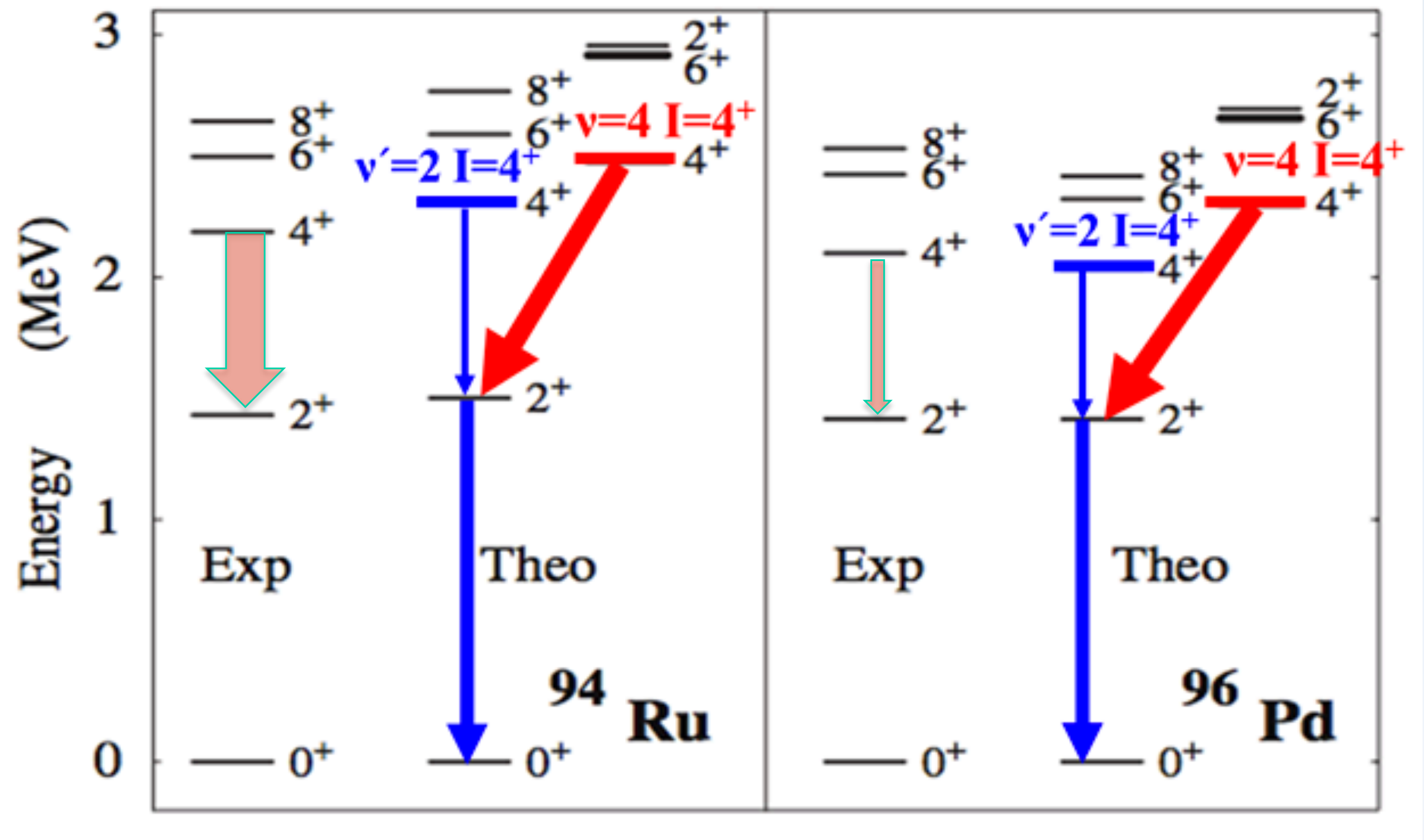
(Received 17 September 2003; published 15 March 2004)

B(*E*2) values from isomeric states near closed shells are discussed in the context of the behavior of seniority conserving transitions induced by even tensor operators. This result provides a signature for the transition from the seniority regime to collective motion that can be of use in identifying shell structure in exotic nuclei.

DOI: 10.1103/PhysRevC.69.034317 PACS number(s): 21.10.Pc, 21.60.Cs, 23.20.Lv, 27.80.+w

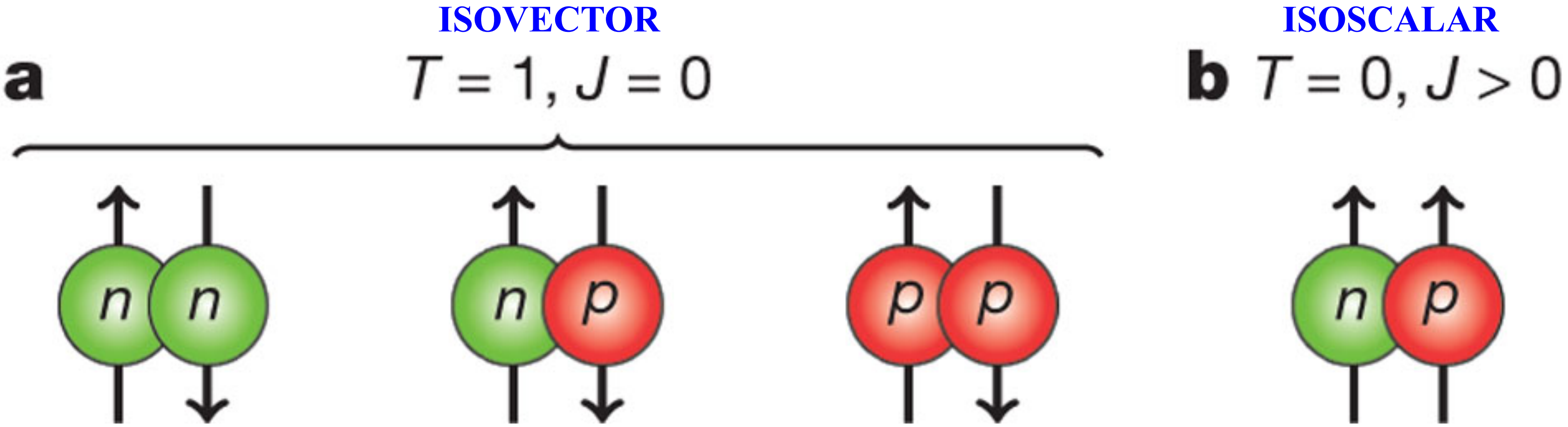


Shell model predictions for semimagic ^{94}Ru and ^{96}Pd: "special" low-lying v=4, I=4^+ state



C. Qi, priv. comm.

Neutron-proton pairing in N = Z nuclei



When approaching N=Z, ”normal” pair correlations may remain or even be extended as neutrons and protons occupy identical quantum states

- Binding energies in e-e and o-o nuclei indicate that **T=1 *np* pairing** is dominant, no evidence for a T=0 (deuteron-like) pair condensate **up to around A≈60**

- Comparison of spectroscopy data with mean-field calculations for A=60-76 nuclei also suggests the presence of a strong isovector (T=1) *np* pair field at low spin, but no evidence for T=0 pairing.

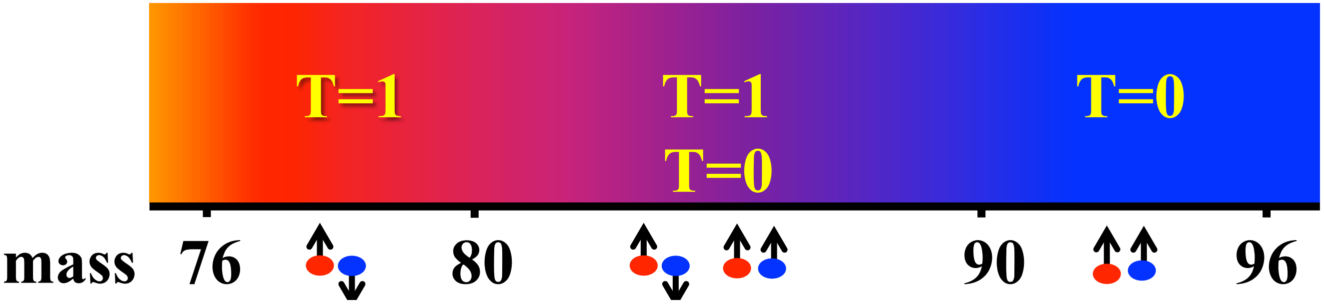
P. Vogel, Nucl. Phys. A662 (2000) 148,
A.O. Macchiavelli et al PRC 61 (2000) 014303R
A Afanasjev, S Frauendorf, Phys. Rev. C 71, 064318 (2005)
S. Frauendorf, A.O. Macchiavelli, Prog. in Particle and Nuclear Physics 78, 24 (2014)

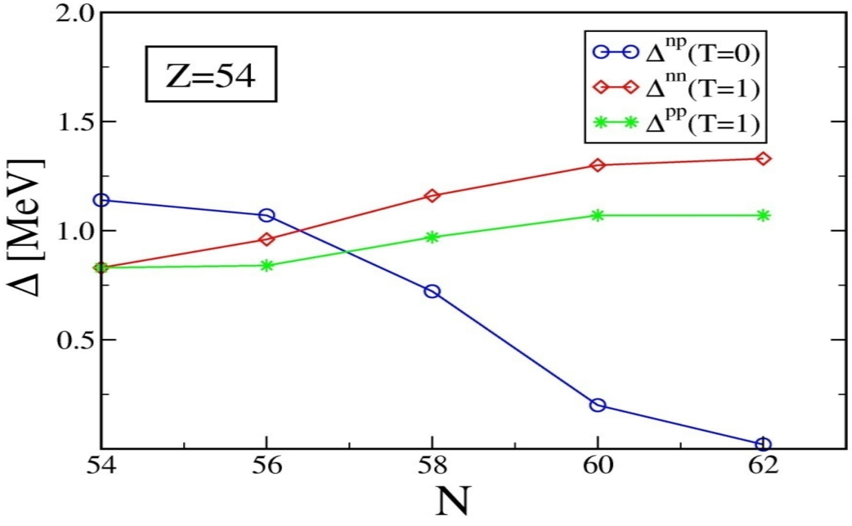
We know the isoscalar effective NN interaction is strongly attractive but can it produce a correlated np pairing condensate???

Predictions for neutron-proton pairing in N = Z nuclei

Does T=0 pairing/ interaction play a role at low or high spin in heavier N=Z nuclei?

A. L. Goodman , PRC 60, 014311 (1999) –
studies of ground states of e-e A = 76-96, N = Z nuclei

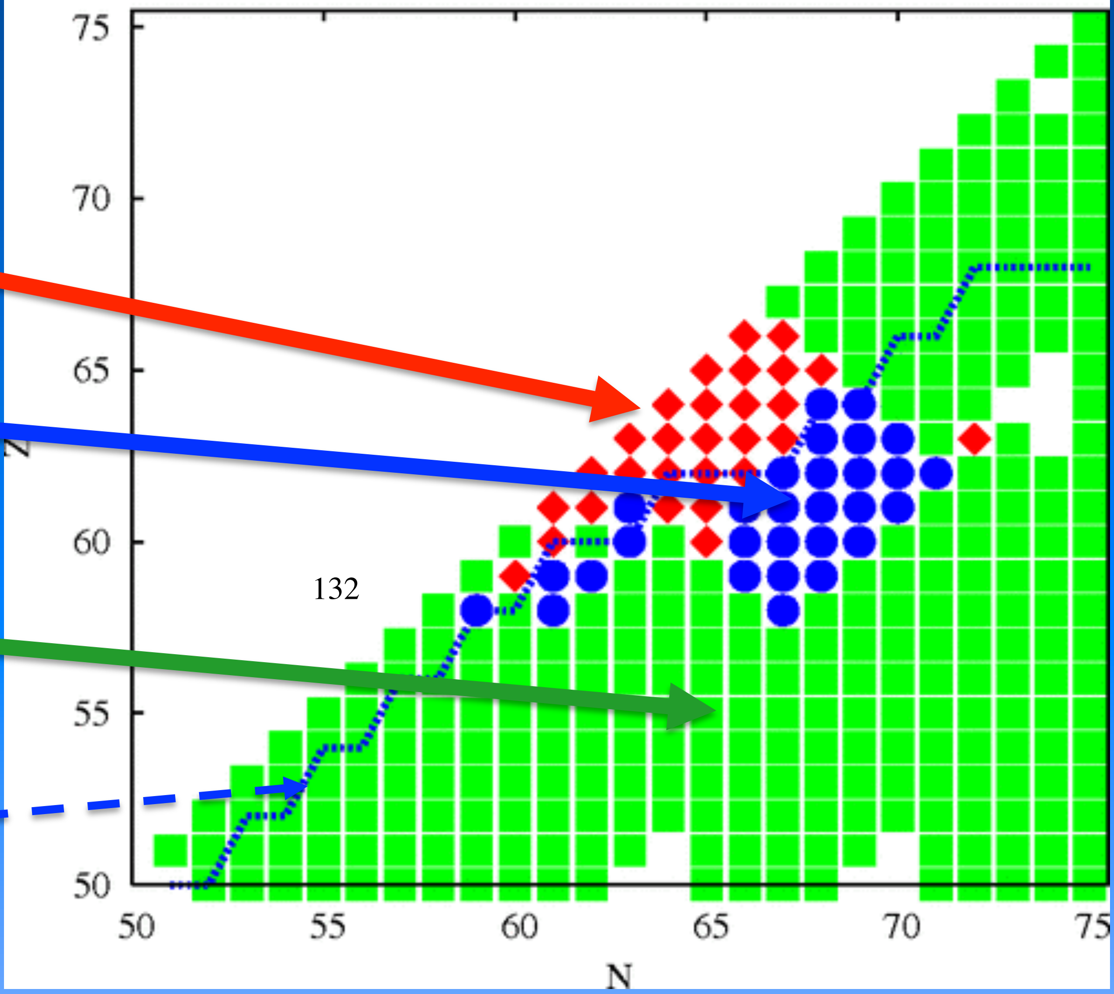




W. Satula,R.Wyss, Phys. Rev. Lett. Vol. 86, 4488 (2001)

The isoscalar (np) pair gap is predicted to increase sharply as N → Z

Island of ground-state isoscalar pairing condensates around $^{132}\mathrm{Dy}_{66}$?



Isoscalar Pairing Condensate

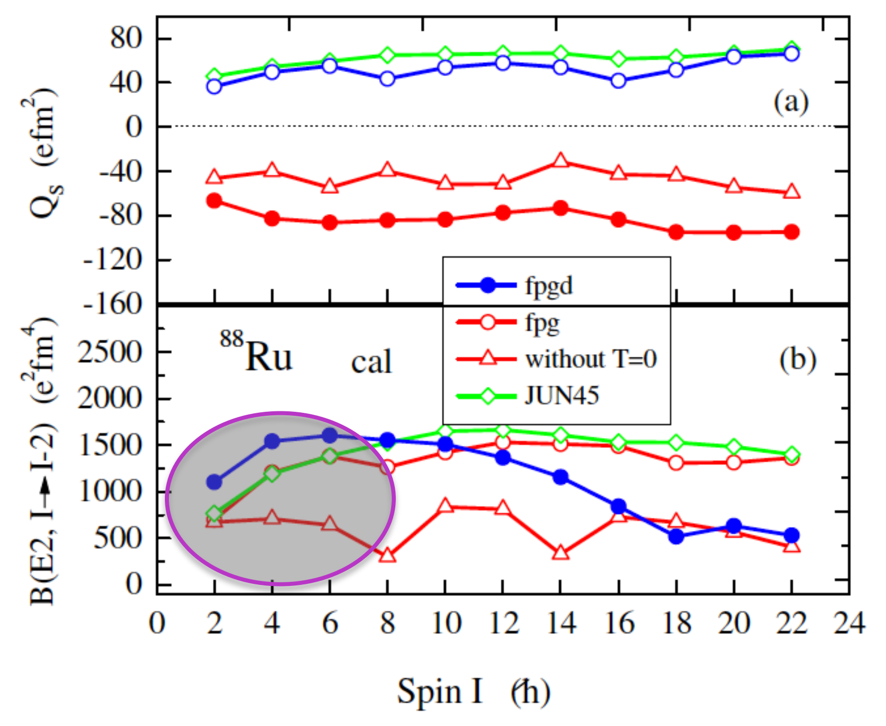
Mixed Pairing Condensate

Isovector Pairing Condensate

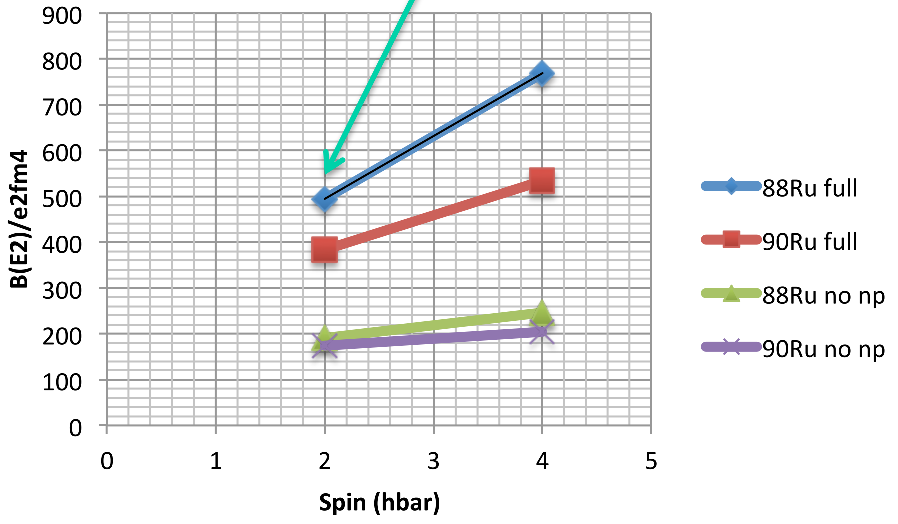
Proton dripline

Taken from
“Mixed-Spin Pairing Condensates in Heavy Nuclei“
A. Gezerlis, G. F. Bertsch, and Y. L. Luo
Phys. Rev. Lett. 106, 252502 (2011)

LSSM calculations and np pairing in ^{88}Ru: Transition rates



Note: $e_p = 1.5$ e $e_n = 1.1$ e



$T_{1/2\text{theo}} = 26$ ps

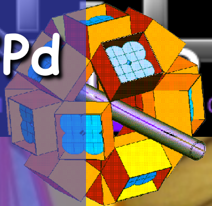
JUN45, $e_p = 1.5$ e $e_n = 0.5$ e

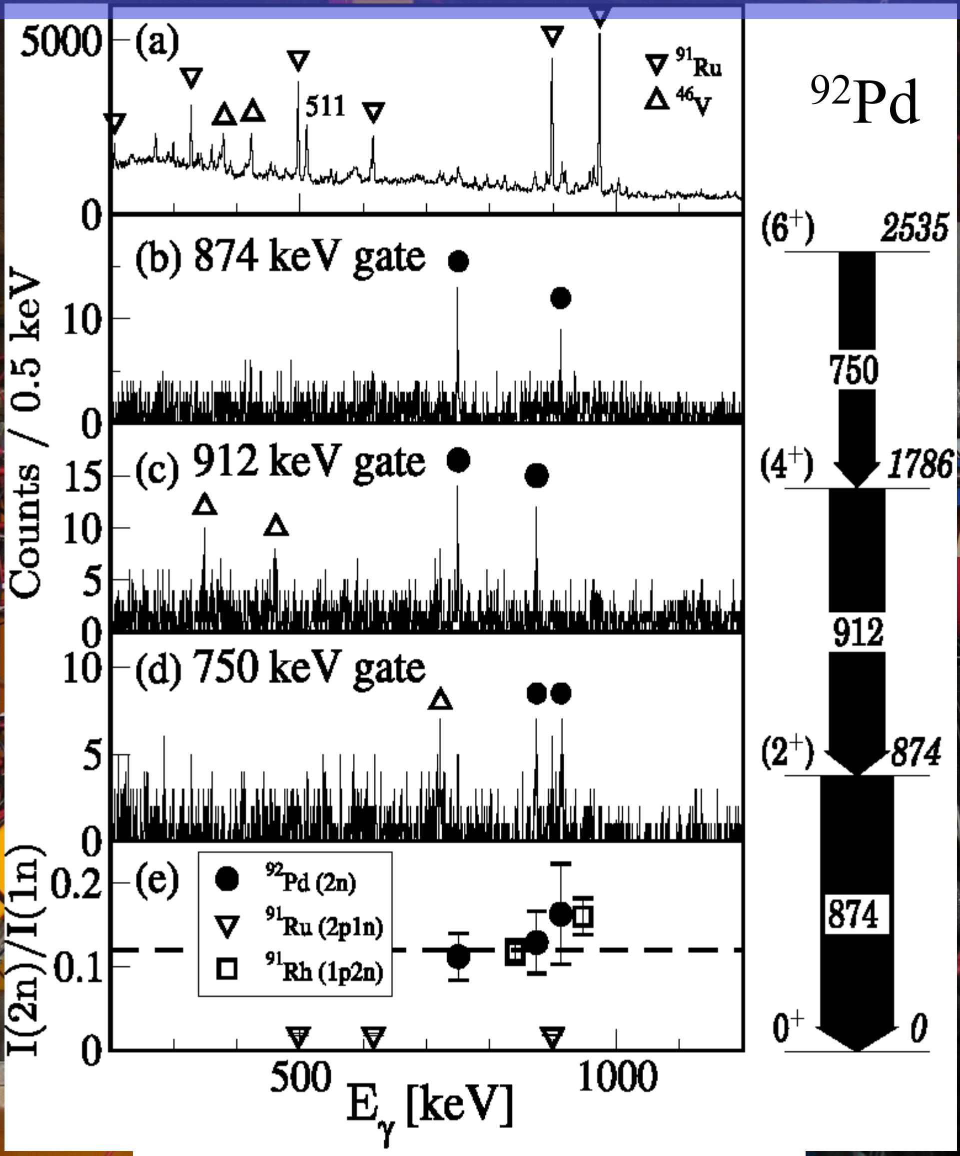
C. Qi, priv. com

Enhancement of high-spin collectivity in N = Z nuclei
by the isoscalar neutron-proton pairing
Kaneko, Sun and de Angelis, Nucl. Phys. A957, 144 (2017)

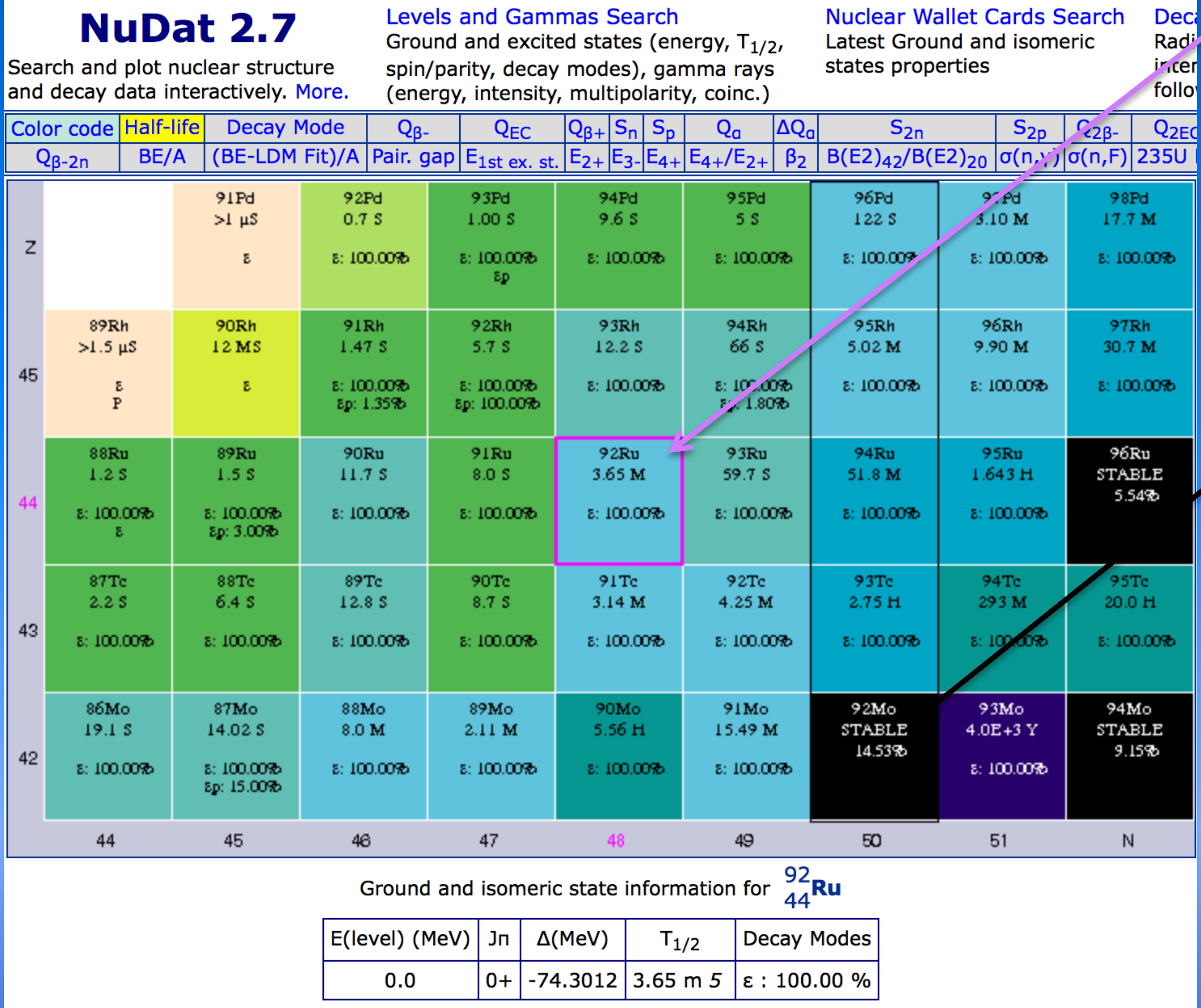
Observation of excited states in the N=Z=46 nucleus ^{92}Pd

EXOGAM + Neutron Wall + Diamant experiment





B. Cederwall et al., Nature **469**, 68 (2011)



NuDat 2.7

Search and plot nuclear structure and decay data interactively. More.

Levels and Gammas Search
Ground and excited states (energy, $T_{1/2}$, spin/parity, decay modes), gamma rays (energy, intensity, multipolarity, coinc.)

Nuclear Wallet Cards Search
Latest Ground and isomeric states properties

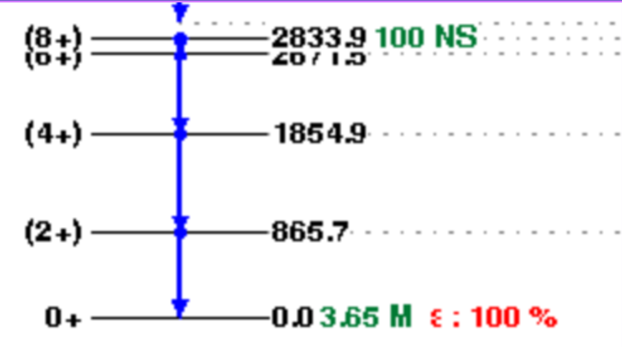
Deca
Radi
inter
follo

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	ΔQ_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}
$Q_{\beta-2n}$	BE/A	(BE-LDM Fit)/A	Pair. gap	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	$\sigma(n,\gamma)$	$\sigma(n,F)$	235U

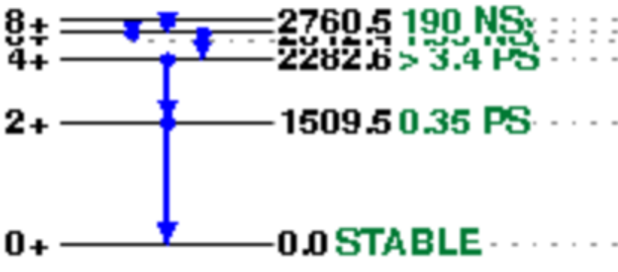
Z		91Pd >1 μS ε	92Pd 0.7 S ε: 100.00%	93Pd 1.00 S ε: 100.00% εp	94Pd 9.6 S ε: 100.00%	95Pd 5 S ε: 100.00%	96Pd 122 S ε: 100.00%	97Pd 3.10 M ε: 100.00%	98Pd 17.7 M ε: 100.00%
45	89Rh >1.5 μS ε P	90Rh 12 MS ε	91Rh 1.47 S ε: 100.00% εp: 1.35%	92Rh 5.7 S ε: 100.00% εp: 100.00%	93Rh 12.2 S ε: 100.00%	94Rh 66 S ε: 100.00% εp: 1.80%	95Rh 5.02 M ε: 100.00%	96Rh 9.90 M ε: 100.00%	97Rh 30.7 M ε: 100.00%
44	88Ru 1.2 S ε: 100.00% ε	89Ru 1.5 S ε: 100.00% εp: 3.00%	90Ru 11.7 S ε: 100.00%	91Ru 8.0 S ε: 100.00%	92Ru 3.65 M ε: 100.00%	93Ru 59.7 S ε: 100.00%	94Ru 51.8 M ε: 100.00%	95Ru 1.643 H ε: 100.00%	96Ru STABLE 5.54%
43	87Tc 2.2 S ε: 100.00%	88Tc 6.4 S ε: 100.00%	89Tc 12.8 S ε: 100.00%	90Tc 8.7 S ε: 100.00%	91Tc 3.14 M ε: 100.00%	92Tc 4.25 M ε: 100.00%	93Tc 2.75 H ε: 100.00%	94Tc 293 M ε: 100.00%	95Tc 20.0 H ε: 100.00%
42	86Mo 19.1 S ε: 100.00%	87Mo 14.02 S ε: 100.00% εp: 15.00%	88Mo 8.0 M ε: 100.00%	89Mo 2.11 M ε: 100.00%	90Mo 5.56 H ε: 100.00%	91Mo 15.49 M ε: 100.00%	92Mo STABLE 14.53%	93Mo 4.0E+3 Y ε: 100.00%	94Mo STABLE 9.15%
	44	45	46	47	48	49	50	51	N

Ground and isomeric state information for $^{92}_{44}$Ru

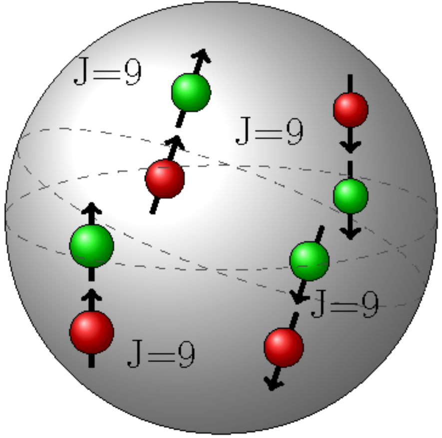
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	-74.3012	3.65 m 5	ε : 100.00 %



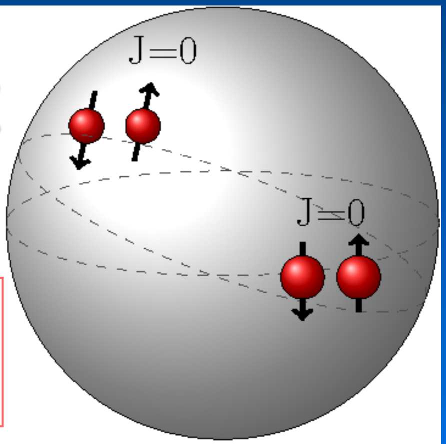
Arnell et al., Z.P.A. 1993



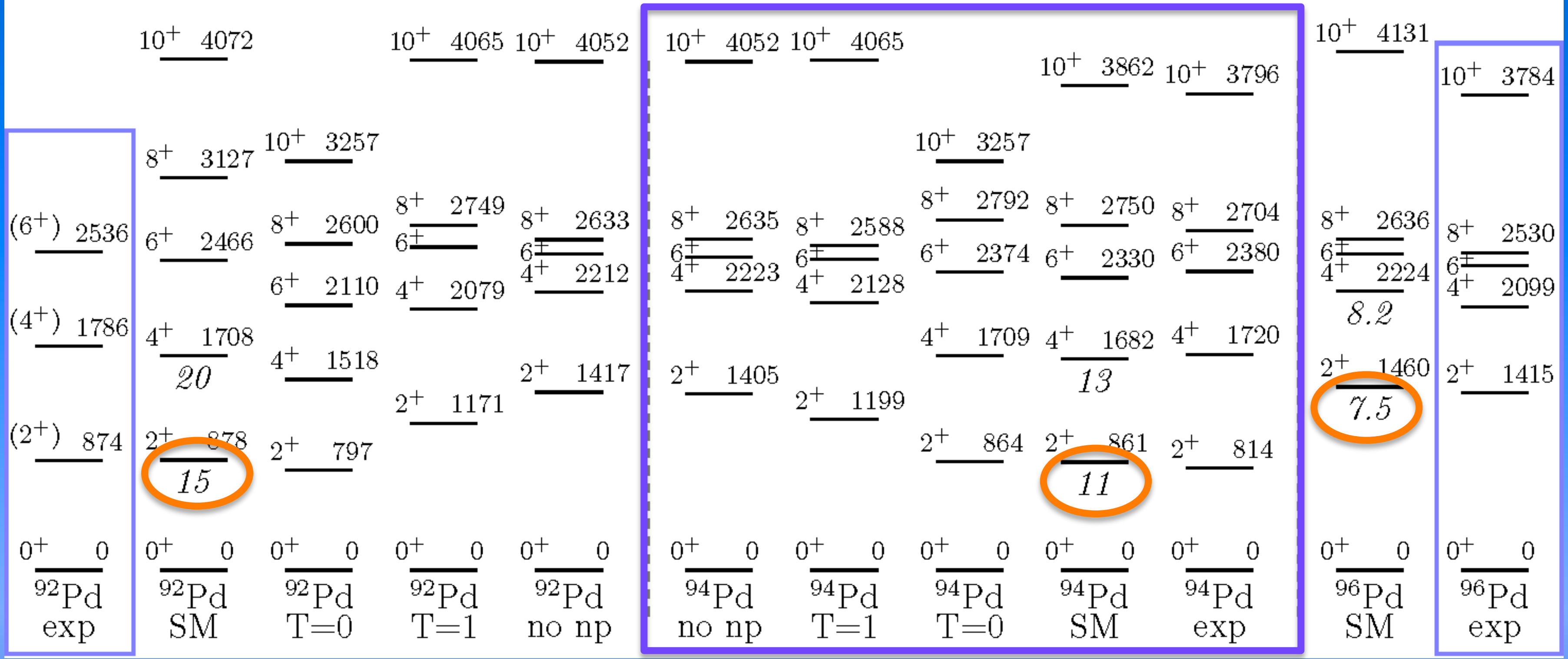
D. Ward et al., AECL rep. 1971



Pd level systematics near N=Z - effects of np interactions

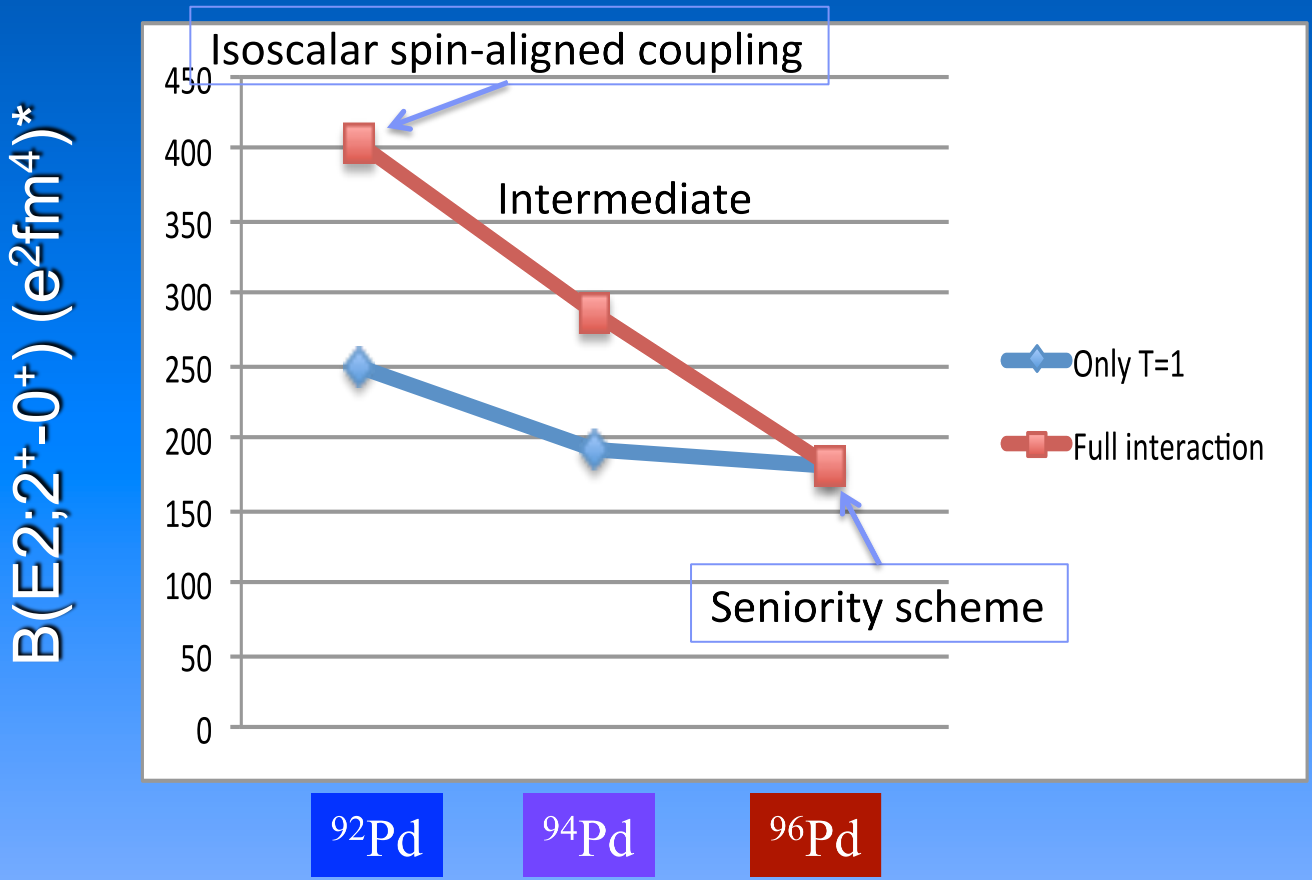


Calculations performed in several model spaces,
i.e., 0g9/2, 0g9/2-1p1/2 and 0g9/2-1p1/2-0f5/2-1p3/2
which all give very similar results .
Int. parameters determined to reproduce exp energies in ^{94,95}Pd, ^{93,94}Rh



Taken from B. Cederwall et al., Nature 469, 68 (2011)

LSSM calculation, fpg valence space ($f_{5/2}$, $p_{3/2}$,$p_{1/2}$, $g_{9/2}$) (all shells between 28 and 50) C. Qi



Isoscalar spin-aligned coupling

Intermediate

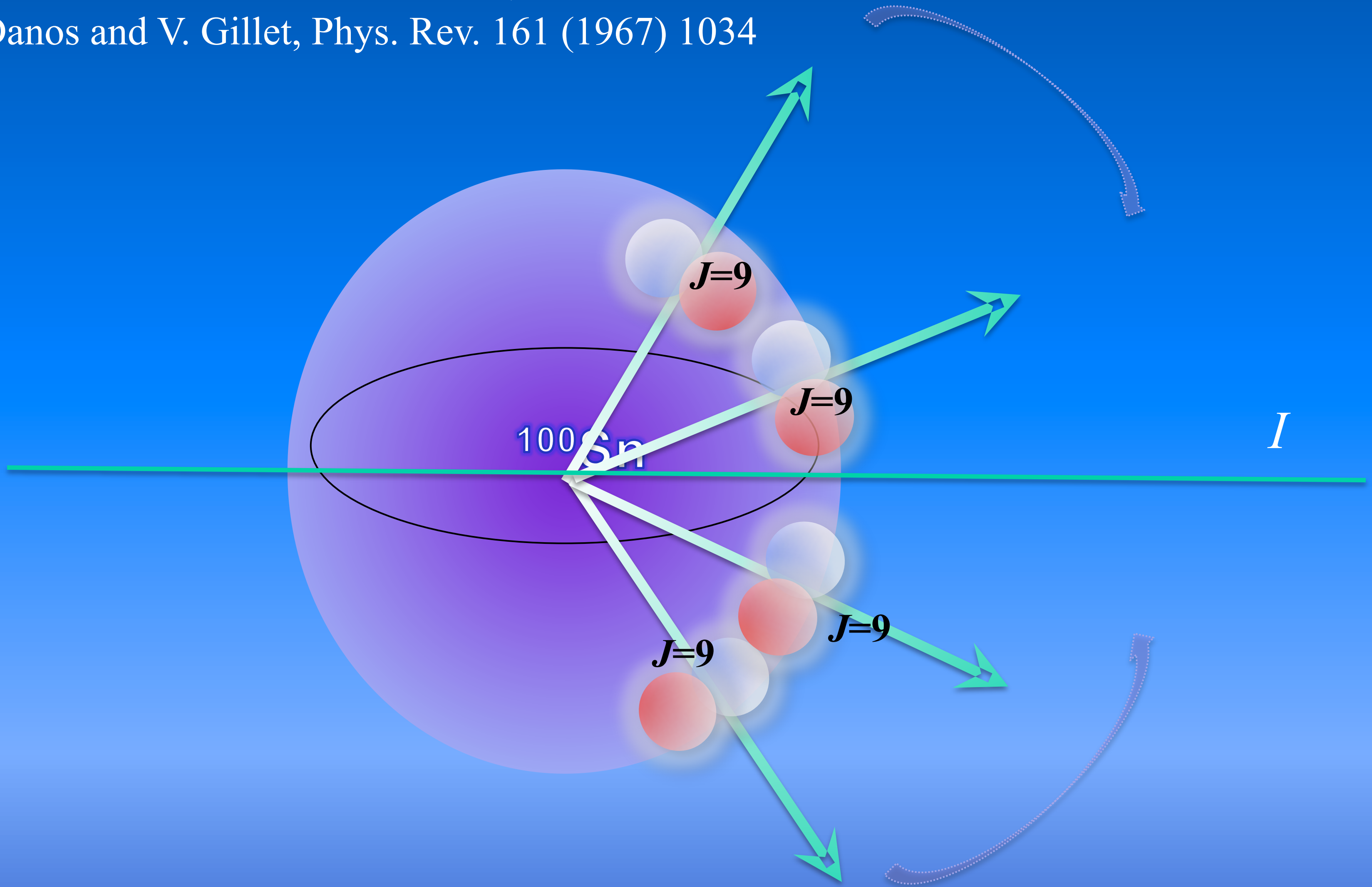
Seniority scheme

- 1 W.U. ~ 25 e^2fm^4 here
- Effective charges, e_p=1.5e, e_n=0.5e
  M. Honma et al, Phys Rev C 80 064323 (2009)

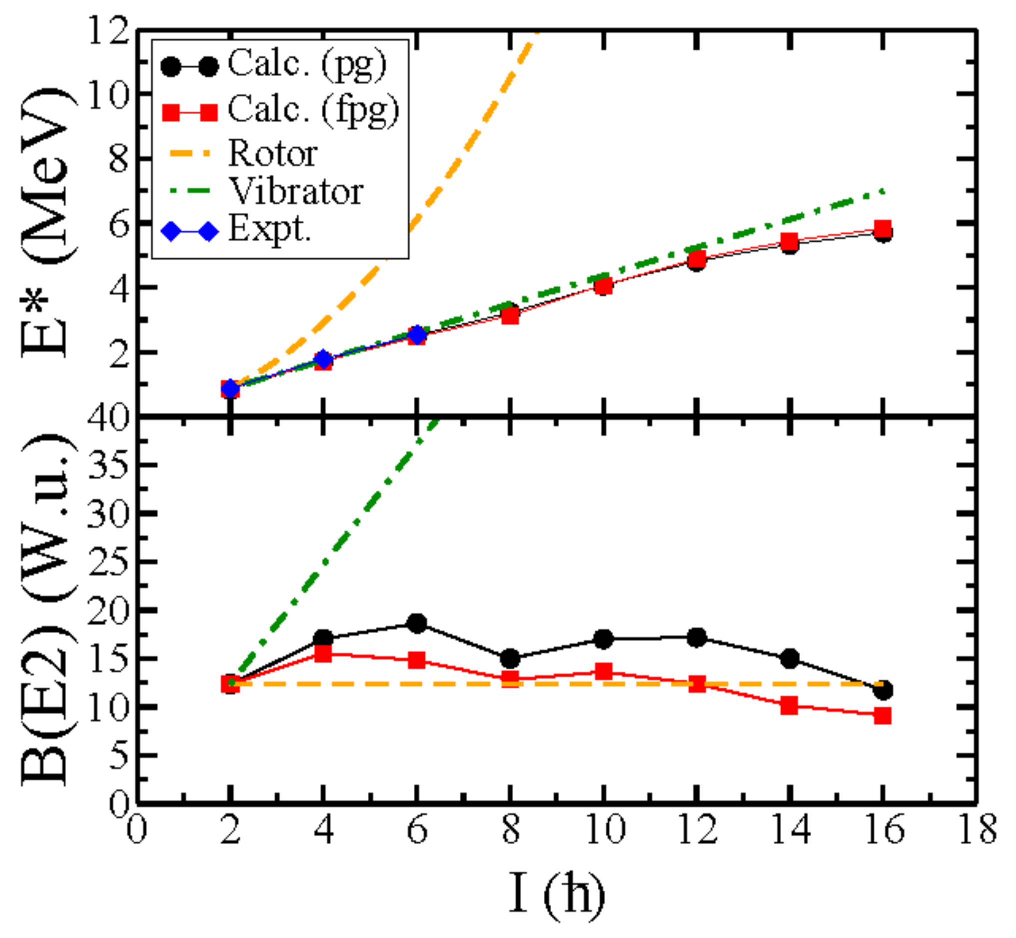
Generation of angular momentum in the isoscalar spin-aligned coupling scheme (^{92}Pd)

Similarities with "stretch scheme"

M. Danos and V. Gillet, Phys. Rev. 161 (1967) 1034

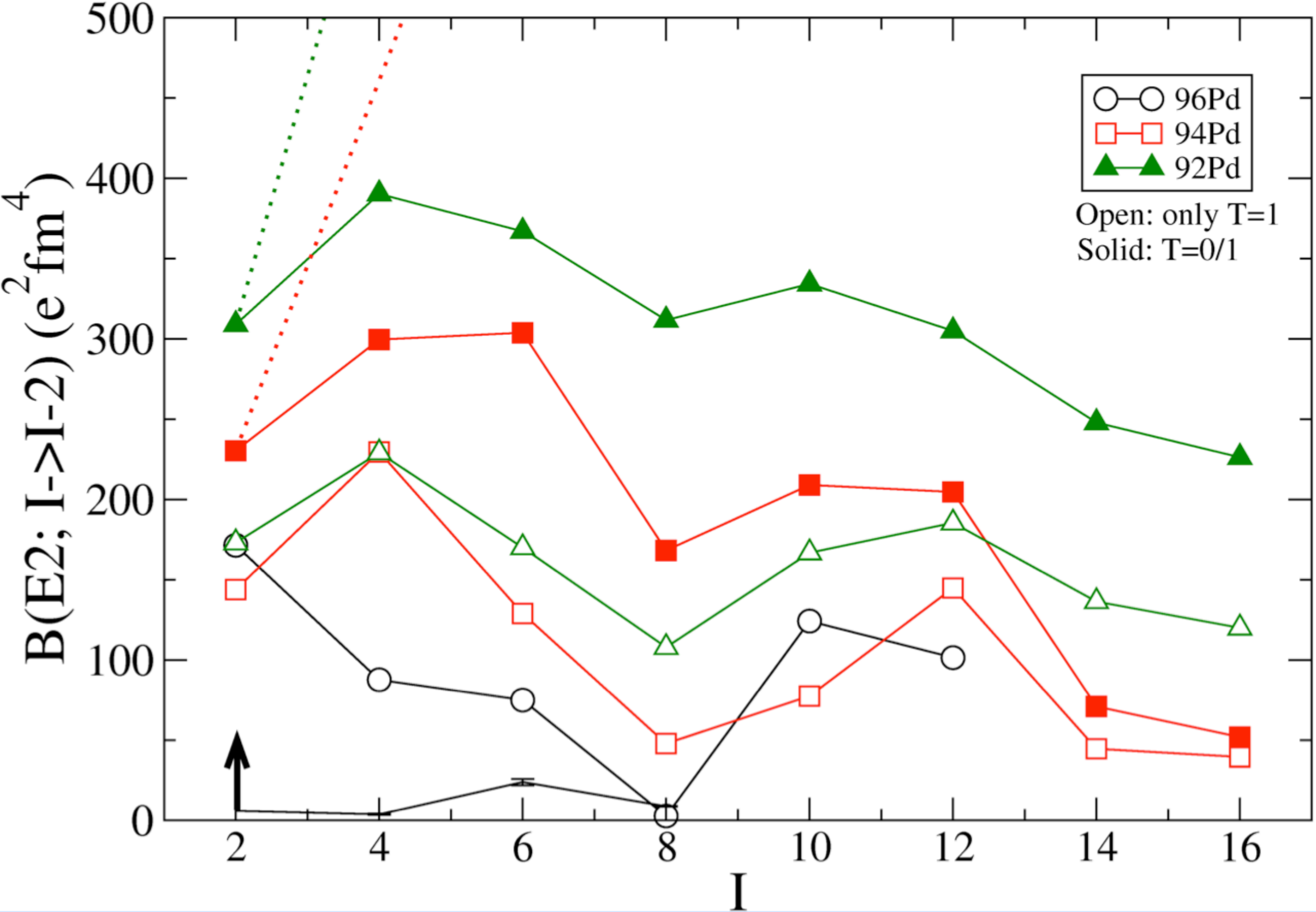


^{92}Pd



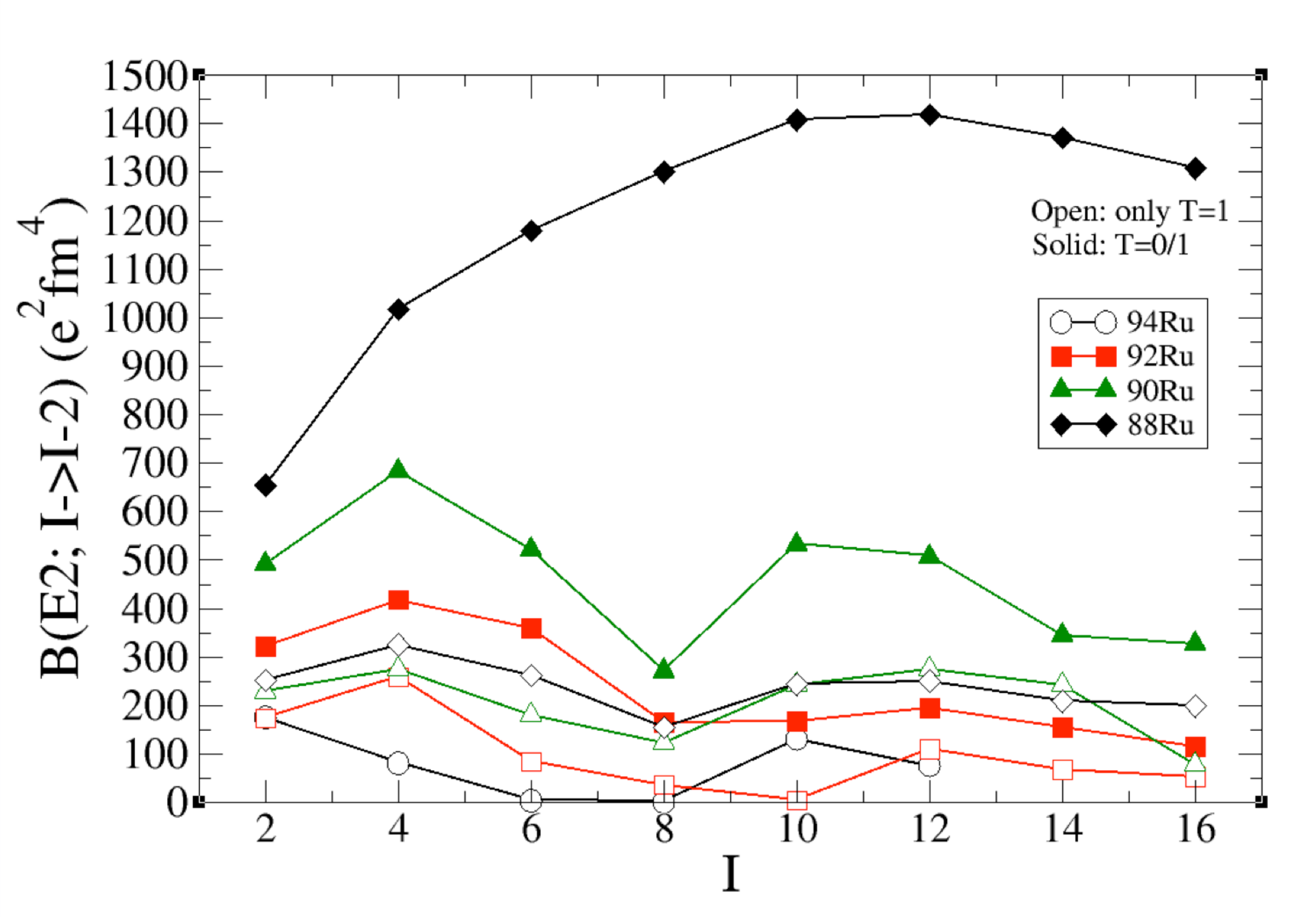
Shell model spectra and B(E2; I → I − 2) values of ^{92}Pd calculated within the $1p_{3/2}0f_{5/2}1p_{1/2}0g_{9/2}$ space (fpg) and the $1p_{1/2}0g_{9/2}$ space (pg). (B. Cederwall et al., Nature 469, 68 (2011); C. Qi Phys. Rev. C 84, (2011))
The two dashed lines show the predictions of the geometric collective model normalized to the 2^+_1 state

Pd isotopes: SM calculations



Calculated B(E2;I→I-2) values as a function of angular momentum in ^{92,94,96}Pd. The calculations have been performed in the fpg space with the JUN45 interaction using standard effective charges. The theoretical calculations for the spectra of ^{92,94}Pd include, in addition to full neutron-proton interactions (solid symbols), also results for pure T=1 neutron-proton (open symbols) interactions. Dashed lines indicate schematically the prediction for collective harmonic vibration.

Ru isotopes: SM calculations



Calculated B(E2;I→I-2) values as a function of angular momentum in $^{88\text{-}94}$*Ru. The calculations have been performed in the fpg space with the JUN45 interaction using standard effective charges. The theoretical calculations for the spectra of* ^{88,90,92}*Ru include, in addition to full neutron-proton interactions (solid symbols), also results for pure T=1 neutron-proton (open symbols) interactions.*

Open questions:

- Seniority states in the $g_{9/2}$ shell
- What is the relative strength of the isoscalar component of the NN interaction?
- What happens when moving from the N=50 magic shell closure towards the N=Z line?
- Do we find the "standard" behavior of increased quadrupole collectivity?
- Does isovector coupling (i.e. seniority-like structure) prevail?
- Or do we observe effects from a dominance of an isoscalar, "spin-aligned" coupling?

Thank you for your attention